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EVALUATION OF COMFORT LINERS FOR PILOT HELMETS

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13. ABSTRACT *(Maximum 200 words)*
Armstrong Laboratory the Helmet Mounted Systems Technology Section (AL/CFA (HMST)) requested that the Systems Support Division, Materials Behavior and Evaluation Section (WL/MLSE) evaluate several existing pilot helmet comfort liner systems. A database on current custom fit helmet comfort liners did not exist. Armstrong Laboratory needs this database to guide the development of advanced helmet comfort liner systems. This report evaluated three different helmet comfort liner systems. The softest system is a closed cell foam-in-place silicone liner (FIPSL) by GEC Marconi. This system consists of an outer bag into which is foamed a silicone closed cell foam material. The most common currently used system is a Thermoplastic Sheet Liner (TPL) by Gentex. This system consists of four or five sheets of thermoplastic material with hemispherical bumps. The most rigid system is an expoxy coated open-cell foam system called a Thermoformed Liner (TFL) by Kaiser Electronics. Coefficient of friction, compression and creep data are generated on each of the helmet comfort liner materials.

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The Authors contributions to this effort also deserve some explanation. Mark Kistner developed the test plan for this effort, monitored the mechanical testing, and wrote the final report. Robert Cassoni manufactured, machined, and tested all test specimens. Funding for this project was provided by Armstrong Laboratory. Captain Larry Wiley of Armstrong Laboratory provided what they hoped to gain by doing this project. He proposed the project, monitored the project, approved the test plan, and reviewed and added comments to the final report.

SECTION 1.0 INTRODUCTION

Current helmet systems such as the HGU-55/P consist of a multilayer construction. The outer layer is a rigid shell made from organic matrix composite material. Below this layer is an impact absorption layer of polystyrene foam. The purpose of the next layer is to provide a comfortable custom fit to the pilot's head. This layer is called the comfort liner or comfort liner system. Immediately next to the pilot's head is a cloth sanitary liner. The Helmet Mounted Systems Technology Section of Armstrong Laboratory AL/CFA (HMST) requested that the Systems Support Branch, Materials Behavior and Evaluation Section (WL/MLSE), evaluate several existing pilot comfort liner systems. They did not have a database of mechanical properties of these systems. Armstrong Laboratory chose to examine the comfort liner, since this low stiffness layer could cause helmet instability. When night vision goggles are attached, a moment(torque) is caused by the weight of the goggles in high gravitational force (G) maneuvers which may cause the goggles to lose proper alignment with the pilot's eyes. This instability inhibits the pilot's ability to complete his mission and creates a safety hazard. On the other hand, a very stiff comfort liner is good for helmet stability, but poor in pilot comfort. Factors such as helmet weight, strapping system, head contact area, and helmet balance may also affect helmet stability, but were not examined under this effort.

SECTION 2.0 BACKGROUND

In discussions with Capt Wiley of AL/CFA (HMST), he indicated a need for a database to evaluate future advanced comfort liner systems when compared to the properties of the past helmet liner materials. Historically, helmet comfort liner systems have not been designed to a specific set of mechanical property goals, in fact the mechanical properties for these systems were not even measured. Testing was only conducted at the full-scale helmet level. Neary, Bate, Heller and Williams (Ref. 3) measured helmet slippage during voluntary head movement with sensors attached to full scale helmets. Blackwell and Robinette (Ref. 1) examined the comfort and optical stability of three full-scale helmet systems, in which the comfort liner and helmet fit were found to be key design factors in the development of comfortable yet stable helmet systems. Capt Wiley recognized the need to understand the basic mechanical properties of the helmet comfort liner layer. Capt Wiley asked MLSE to evaluate three types of fitted helmet comfort liners. The softest system is a closed cell Foam-in-Place Silicone Liner (FIPSL) system by GEC Marconi. This system consists of an outer bag into which is injected a mixed two part silicone material (mixing and injection is via a hand operated dispensing system) and allowed to foam-in-place. The most common currently used system is a Thermoplastic Sheet Liner (TPL) by Gentex. This system consists of four or five sheets of thermoplastic material with hemispherical bumps. The most rigid system is an epoxy coated open-cell foam system called Thermoformed Liner (TFL) by Kaiser Electronics. These three systems are commonly used as comfort liners for pilot helmets. The advent of helmet mounted-displays and night vision goggles requires that the optics maintain alignment with the pilot's eyes. Several recent references examined the design or use of helmet mounted-displays or night vision goggles (Ref 4,5,7,8,11,12 and 13). Stiffler and Wiley in Ref. 7 define the "fit equation" as:

$$\text{FIT} = \text{comfort} + \text{optical adjustment} + \text{stability}$$

The comfort liner systems are key to two elements of this equation, comfort and stability. However, these factors tend to oppose each other. A helmet liner which is stiff may be good in helmet stability but poor in pilot comfort.

SECTION 3.0 EXPERIMENTAL PROCEDURES

3.1 SPECIMEN PREPARATION

For mechanical property evaluation, the curved surfaces of the fitted helmet liners provided by Captain Wiley caused problems in accurately measuring the mechanical properties. To alleviate this problem, MLSE requested and received additional unformed material from the comfort liner manufacturers. Great care was taken in trying to produce a flat sheet material which simulated the material used in the fitted helmet liner. In the following sections, we will describe the procedures used to produce the test specimens used for this effort.

3.1.1 KAISER TFL

The forming of the Kaiser Electronics TFL was the most straight forward, with the material being heated to 230°F and held for 1/2 hour. This simulates several 5-10 minute fitting cycles. This material is nonrigid when it reaches the forming temperature of 230°F, at which it will drape under its own weight. To produce a flat sheet, the material was sandwiched between two 1/16-in-thick aluminium plates with nonporous teflon sheets for release surfaces. No additional weight or pressure beyond the applied upper plate was needed to maintain a flat surface. After the elevated temperature cure cycle, the material remained at room temperature for at least one week before testing. The purpose of keeping the material at room temperature is to allow shrinkage or thermal stresses created during cure to alleviate.

3.1.2 GEC MARCONI FIPSL

For the GEC Marconi FIPSL, GEC Marconi provided a hand operated dispensing system gun and two component cartridges. When the two components are mixed, the material foams at room temperature. Wood covered with adhesive backed teflon tape was used for the mold. The mold cavity size was calculated by measuring the density of a representative piece of silicone foam out of a fitted helmet liner, and estimating the weight of the material contained in a two component cartridge. The material was processed by using the hand operated dispensing gun to empty the contents of one cartridge into an 8-in x 8-in x 0.5-in mold cavity. After the foam had been in the mold for at least 1/2 hour, the mold top was removed and the material was allowed to sit in a ventilation hood for 24 hours to allow residual foaming agent to evaporate. This material was noticed to have density variations throughout the sheet. Similar density variations were noticed in the fitted helmet liners.

3.1.3 GENTEX TPL

The Gentex TPL (Thermoplastic Liner) is the most difficult to form into a flat sheet which simulates the material out of a fitted helmet liner. The unfitted TPL consists of four sheets of ethylene vinyl acetate with hemispherical 0.3-in diameter bubbles. The layers are arranged in a convex-concave-convex-concave arrangement and ultrasonically bonded at two attachment points. Both attachment points are closely spaced and are placed above the crown of the pilots head in a fitted TPL. In the fitted helmet, the thickness of the comfort liner varied from 0.1 to 0.3 inch with the thinnest and most compacted region being on the crown of the pilots head. The 0.2-in-thick molded sheets were determined to be the most representative of the fitted system. After examination of some fitted TPLs, it was noticed that the sheet closest to the pilots head appeared to be more wrinkled. This indicated an applied compression or shear loading from the side to the crown of the head, since the layers are initially bonded at a spot which sits above the crown of the pilot's head. The outer layer appeared relatively smooth, as if a tension or shear was applied from the top-center of helmet to the lower perimeter. To simulate the stresses that occur during forming, we cut pieces from regions of the unfitted comfort liners with some initial curvature. This curvature aided the forming operation, since as the sheet flattens out during processing, one side is in compression while the other is in tension. The processing operation consisted of preheating an oven to 212°F. A thermocouple was placed between the second and third layer and the layup placed between two sheets of nonporous teflon. Once the oven had stabilized at 212°F, the comfort liner assembly was placed in the center of the oven. After the thermocouple in the comfort liner assembly reached 195° F, the assembly was removed from the oven and moved into a mold which consisted of a top caul plate with stops at 0.197-in from the bottom surface. The top caul plate was applied to the comfort liner material assembly and the caul plate was manually pressed until the stops were reached. This process produced material which looked very similar to material taken from a fitted comfort liner.

3.1.4 SPECIMEN MACHINING

Specimens where cut out of the FIPSL and TPL by using a sharp scalpel. For the TFL system, the specimens were machined by using a band saw for square specimens or a diamond coated hole saw in a drill press for round specimens. The drill press depth was set such that the specimen's lower surface was not penetrated. After drilling the specimens could be easily removed by hand applied pressure. If completely drilled through the thickness, the specimen would not easily release from the hole saw.

3.2 MECHANICAL TESTING

Mechanical testing consisted of compression, creep, and coefficient of friction testing. The traditional test methods used for plastics and cellular plastics were adapted for testing of the comfort liners. The comfort liners required testing in the low load region, typically 20-lb or less; for this testing a Sintech Low Load Test Machine owned by the Structural Materials Branch, Composites Section proved to be useful. The advantage of using this machine is that the load cells were designed for low load testing and ranged from 350 grams to 1000 pounds full scale load capacity.

3.2.1 COMPRESSION TESTING

The compression test method used was ASTM D 1621 with a circular geometry specimen. Due to the limited amount of material available, the diameter of the compression specimen was reduced from that called for in the standard. The diameter of the compression specimens used was 1.5-in while the test standard called for a 2.26-in to 2.76-in diameter. From prior testing of foam materials, experience shows little effect upon compression properties by decreasing the specimen diameter. The test fixture consisted of compression plates with the lower compression base having a spherical seat. Due to the low stiffness of the materials tested, it was not possible to use strain gages or to attach an extensometer. Elongation was measured by crosshead displacement.

3.2.2 CREEP TESTING

The creep testing was done under compression loading, since this is the primary loading in use. Compression load was used to simulate the helmet weight, strap pull, and an applied 9G load. A weight of 5-lb, strap pull of 10-lb, and 9G loading of 45-lb was used to estimate the worst case applied compression loading. This total load is assumed to be distributed over the area of the pilot's head. Calculating the cross-sectional area of the head at the glabella region (a section at the eyebrows parallel to the ground) from a diagram in Ref. 2 gives roughly 42 square inches. The resulting stress is approximately 1.4 pounds per square inch (psi). In actual loading situations, the compression load is usually not uniform. To be conservative, we increased the loading by a factor of two to 2.8 psi. Using a 5-lb dead weight, the resulting specimen loading is 2.8 to 3.1 psi. The range of numbers is caused by slightly different specimen areas. The creep tests were conducted for 48 hours at ambient conditions and 7 to 8 hours at elevated temperatures. An oven sufficient for the elevated temperature creep testing was not available, so one was made. We used a metal cylinder insulated with fiberglass cloth, then added a resistance heating ribbon. The temperature was controlled by using a rheostat to control the voltage to the ribbon. This oven proved accurate to +/- 2°F. Due to the concerns over the safety and reliability of this oven, it was only used while it could be monitored. Thus time at the elevated temperature was set at 7 to 8 hours, so the oven used for this test could be monitored during the work day. This test time was judged to be a more severe test than the comfort liner would see in use, since high G loadings would be applied for only short times as the pilot maneuvers his aircraft. A diagram of the loading fixture is given in Figure 1.

3.2.3 COEFFICIENT OF FRICTION TESTING

For the coefficient of friction testing, MLSE developed a fixture similar to the type C defined per ASTM D 1894-93. This standard was developed for plastic film, but works for the helmet comfort liner materials if care is taken while setting up the test. Since the helmet comfort liner systems are much thicker (up to 0.6-in thick) and are of low stiffness, care must be taken to properly align the friction sled and applied weight. The setup used in this study varied from ASTM D1894-93 type C in that the moving crosshead is above rather than below the test specimen. A diagram of the test setup is shown in Figure 2. Testing was performed using a 1-lb weight normal force via a weight applied to the moveable sled. For the coefficient of friction tests, some flat sheets of impact resistant liner were obtained from Gentex and Sanitary Liners from Captain Wiley.

3.2.4 DENSITY MEASUREMENT TECHNIQUE

Density measurements were taken using ASTM D1622-88. Care must be taken measuring the specimen dimensions so that the material is not compressed. For nonuniform material, the density measurements were taken at low and high density regions. This was done to indicate the range of densities for the material.

SECTION 4.0 RESULTS AND DISCUSSION

4.1 COMPRESSION TESTING RESULTS

The results of the compression testing are shown in Table 1 and comparative stress-strain curves are given in Figure 3. The Kaiser TFL was the most rigid followed by the Gentex TPL and the GEC FIPSL. The TFL comfort liner was the only one to indicate failure as a drop in load during compression. The other two liners were ductile enough that the load continued to increase as compression platens approached each other. The results of the elevated temperature testing indicated that the Gentex TPL and Kaiser Electronics TFL moduli were decreased by elevated (160°F) temperature testing; the GEC Marconi FIPSL showed increased modulus with temperature. The behavior of the GEC material may be explained by noting that this material is a closed cell foam with gas filled cells. As this gas is heated, it applies pressure to the cell walls which can increase the compression modulus in the bulk of the material. When specimens of this material were removed from the test chamber while still warm, it appeared that the gas in the cell walls had indeed expanded. In Appendix B, compression load-displacement curves are given for each material and test condition.

4.2 CREEP TESTING RESULTS

Results are presented in Table 2. At room temperature, some deflection due to application of the weight was noticed. After 48 hours at ambient, the TPL indicated the most creep at 4.3% followed by the TFL and FIPSL at 1.7%. At the elevated temperature of 120°F, all of the comfort liners indicated a larger value of creep. The Gentex TPL exhibited the most creep at 7.1%, followed by the GEC Marconi Foamed-in-Place Liner at 2.8%, and the Kaiser Electronics TFL at 2.0%. All of the comfort liners had some residual set after the creep test. The amount of residual set was greater for the 7 to 8 hours at 120°F versus 48 hours at ambient. At 7 to 8 hours at 120°F, the GEC Marconi FIPSL indicated the least with 0.8%, followed by the Kaiser Electronics TFL at 2.6%, and the Gentex TPL at 6.2%. Overall the Gentex TPL did not preform as well as the GEC Marconi Foamed-in-Place Liner or the Kaiser Electronics TFL in creep behavior.

4.3 COEFFICIENT OF FRICTION TESTING RESULTS

The results of the coefficient of friction testing are presented in Table 3 and are graphically compared in Figure 4. For the Gentex TPL, the lowest friction mode is between the impact liner and the TPL. In the actual helmet, the effective coefficient between these layers may be increased by the application of double sided adhesive tape or Velcro attachment strips. The coefficient of friction was lowest for

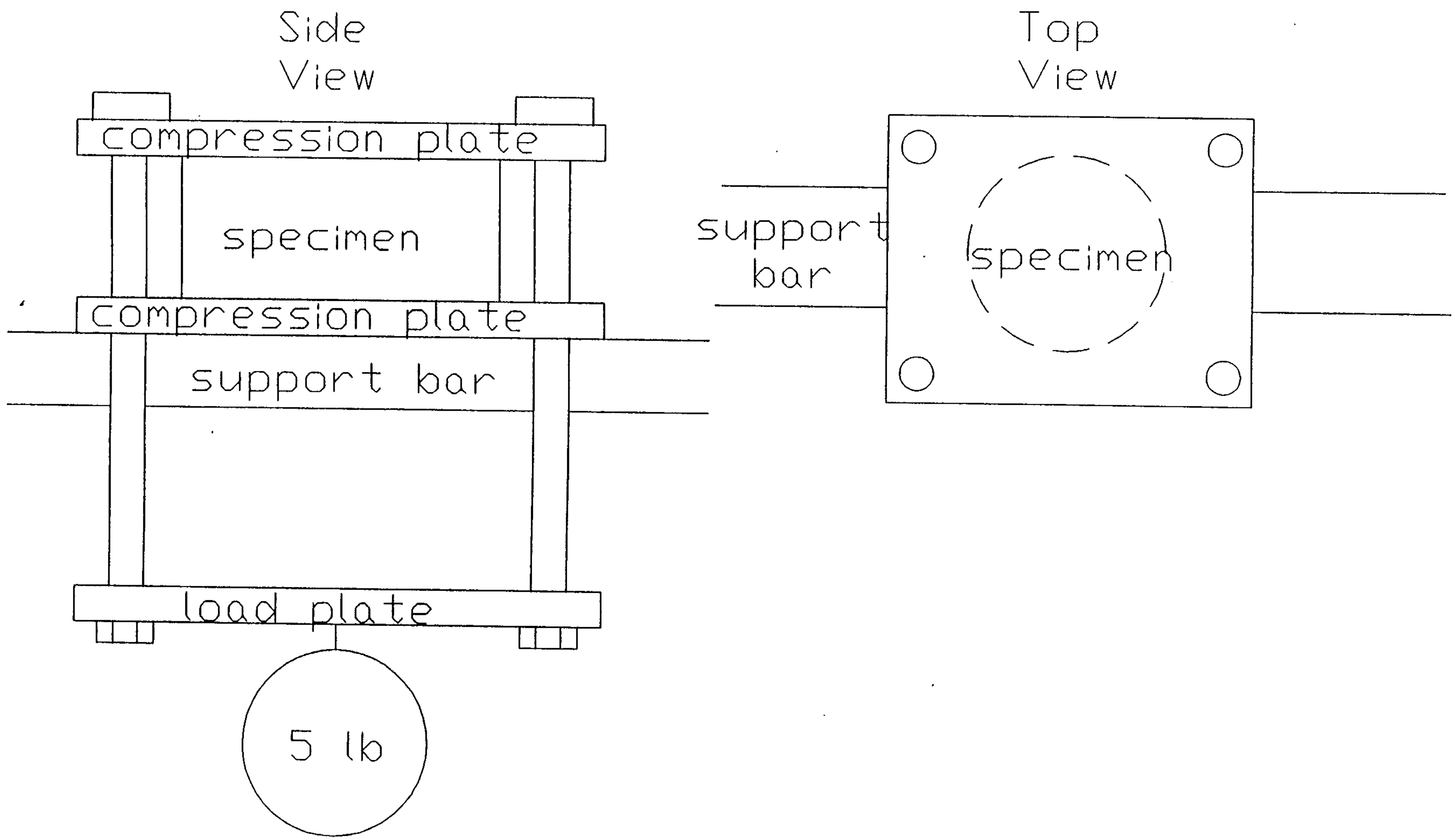

Figure 1. Creep Test Setup

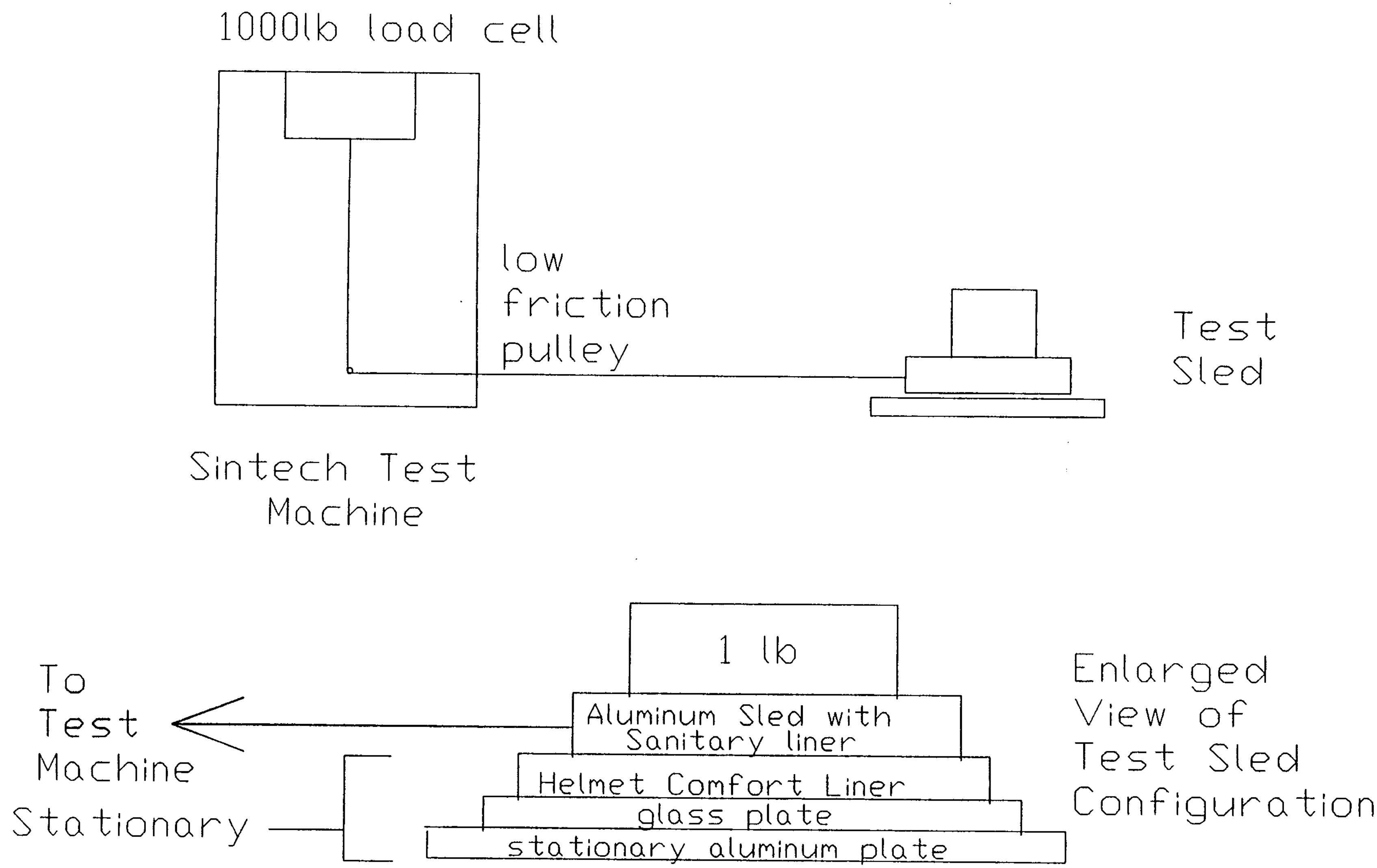

Figure 2. Coefficient of Friction Test Setup

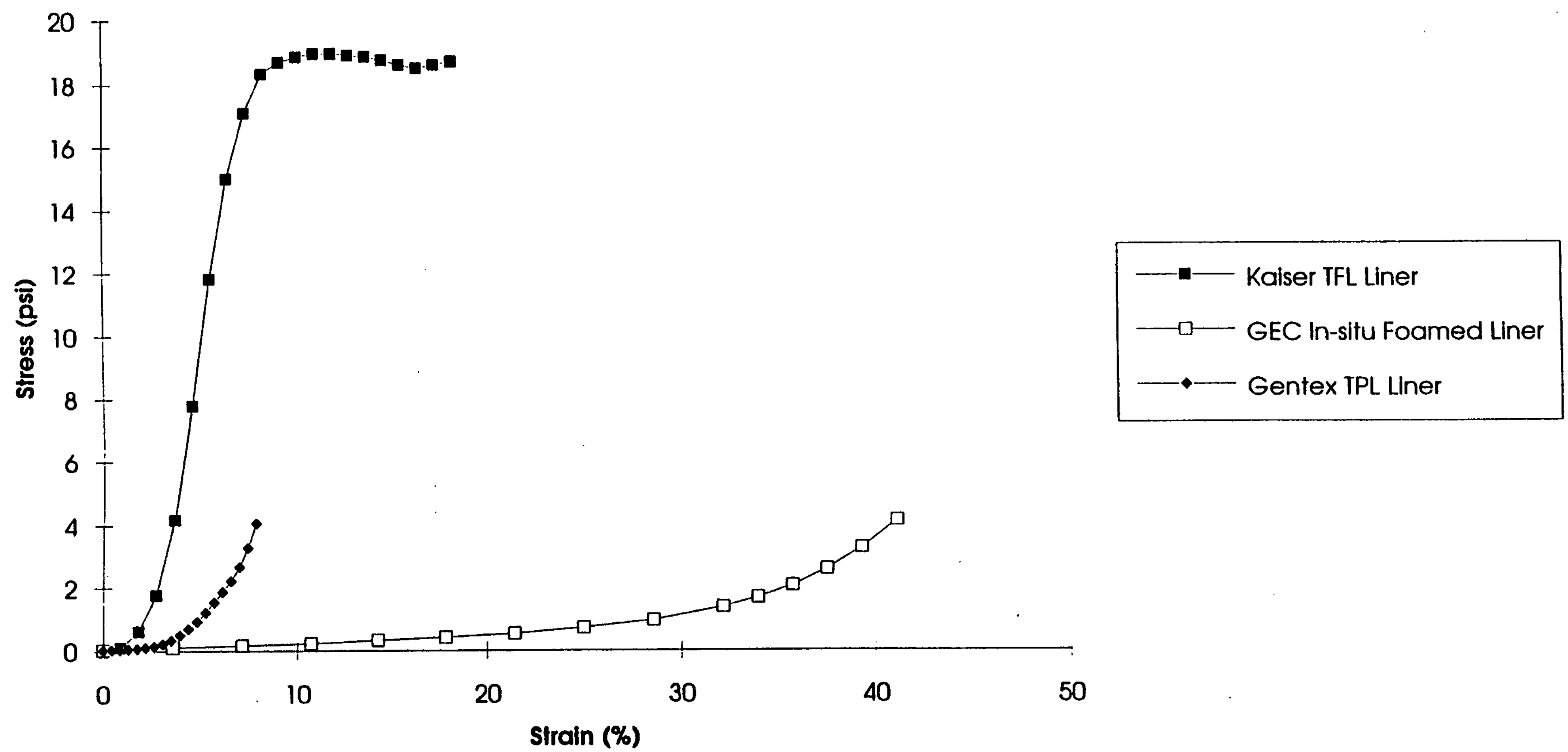

Figure 3. Comparison of Compressive Stress-Strain Curves

Table 1. Flatwise Compression Test Result Summary

GENTEX BUBBLE LINER

Specimen	Age Conditions	Test Conditions	Area (sq in)	Load (lbs)	Strength (psi)	(0-0.01in) Modulus1 (psi)	(0.03-0.04in) Modulus2 (psi)	Best Fit Modulus (psi)	Date	Comments
TP-C-1	None	R.T.	1.615	n/a	n/a	18.38	58.2	n/a	22-Jun-94	No Yield
TP-C-2	"	"	1.631	n/a	n/a	24.94	44.88	n/a	"	"
TP-C-3	"	160F	1.626	n/a	n/a	4.99	15.98	n/a	21-Jul-94	"
TP-C-5	Saline Exp.	R.T.	1.599	n/a	n/a	25.1	37.8	n/a	28-Jun-94	"
TP-C-7	"	160F	1.611	n/a	n/a	12.98	20.02	n/a	21-Jul-94	"

KAISER ELECTRONICS THERMOFORMED LINER

Specimen	Age Conditions	Test Conditions	Area (sq in)	Load (lbs)	Strength (psi)	(0-0.01in) Modulus1 (psi)	(0.03-0.04in) Modulus2 (psi)	Best Fit Modulus (psi)	Date	Comments
TF-C-1	None	R.T.	1.617	25.5	15.8	149.4	134.5	284	24-Jun-94	No Yield
TF-C-2	"	"	1.622	29.25	18.03	132.5	215.9	343.5	"	"
TF-C-3	"	160F	1.615	19.5	11.93	41.46	177.7	177.7	20-Jul-94	"
TF-C-5	Saline Exp.	R.T.	1.586	27.5	17.3	102.1	236.1	295.1	28-Jun-94	"
TF-C-7	"	160F	1.783	16.2	9.88	95.91	130.8	196.2	20-Jul-94	"

GEC MARCONI SILICONE LINER

Specimen	Age Conditions	Test Conditions	Area (sq in)	Load (lbs)	Strength (psi)	(0-0.01in) Modulus1 (psi)	(0.03-0.04in) Modulus2 (psi)	Best Fit Modulus (psi)	Date	Comments
S-C-1	None	R.T.	1.817	n/a	n/a	10.83	6.31	10.83	22-Jun-94	No Yield
S-C-2	"	"	1.81	n/a	n/a	8.87	5.55	8.87	"	"
S-C-3	"	160F	1.846	n/a	n/a	15.65	12.58	10.56	20-Jul-94	"
S-C-5	Saline Exp.	R.T.	1.744	n/a	n/a	5.5	11.01	11.01	28-Jun-94	"
S-C-7	"	160F	1.602	n/a	n/a	12.48	18.26	14.53	20-Jul-94	"

the Gentex TPL when compared with the Kaiser Electronics TFL and the GEC FIPSL. The GEC FIPSL had the next largest coefficients of friction. For the GEC FIPSL, a large difference was noticed at the comfort liner to sanitary liner interface when saline was added. The coefficient of friction drops to 36% of its dry value. For the Kaiser Electronics TFL, the open cell structure of the comfort liner tended to dig into the sanitary or impact resistant layer. Post testing visual examination of the impact resistant layer when tested with the TFL showed deep surface abrasions. The results for the TFL comfort liner to sanitary liner were the highest values obtained, but the failure mode obtained did not provide a valid coefficient of friction number. The failure was a tensile tearing of the sanitary liner. Plots of the extension versus frictional force are given in Appendix A. The coefficient of friction was calculated by taking the load value just prior to major drops in load, averaging these values, and dividing by the applied normal force.

4.4 DENSITY RESULTS

The results of the density measurements are given in Table 4. The TFL liner has the lowest density. The GEC Marconi FIPSL was noticed to have regions of high and low density, resulting in a large standard deviation in the average density.

Table 2. Creep Data Summary

GENTEX BUBBLE LINER

Specimen	Test Conditions	Area (sq in)	Stress (psi)	2hr loaded % creep	4hr loaded % creep	25hr loaded % creep	48hr loaded %creep	48hr unloaded %Res. set
TP-CR-1	R.T.	1.699	2.94	4.37	5.46	5.46	4.37	2.59

Specimen	Test Conditions	Area (sq in)	Stress (psi)	1hr loaded % creep	2hr loaded % creep	4hr loaded % creep	6hr loaded %creep	8hr loaded % creep	8hr unloaded %Res. Set
TP-CR-3	120F	1.613	3.1	4.37	5.46	7.1	8.2	7.1	6.15

KAISER ELECTRONICS THERMOFORMED LINER

Specimen	Test Conditions	Area (sq in)	Stress (psi)	4hr loaded % creep	25hr loaded % creep	48hr loaded %creep	48hr unloaded %Res. set
TF-CR-1	R.T.	1.595	3.14	0.35	1.75	1.23	0.52

Specimen	Test Conditions	Area (sq in)	Stress (psi)	1hr loaded % creep	2hr loaded % creep	3hr loaded % creep	4hr loaded % creep	5hr loaded %creep	7hr loaded % creep	7hr unloaded %Res. Set
TF-CR-3	120F	1.59	3.14	1.22	1.22	1.22	1.74	1.74	2.09	2.55

GEC MARCONI SILICONE LINER

Specimen	Test Conditions	Area (sq in)	Stress (psi)	4hr loaded % creep	25hr loaded % creep	48hr loaded %creep	48hr unloaded %Res. set
S-CR-1	R.T.	1.772	2.82	1.19	1.19	1.67	0.38

Specimen	Test Conditions	Area (sq in)	Stress (psi)	1hr loaded % creep	2.5hr loaded % creep	4.5hr loaded % creep	7.5hr loaded % creep	7.5hr unloaded %Res. Set
S-CR-3	120F	1.723	2.902	2.27	2.83	3.68	2.83	0.81

Table 3. Tabular Values for Coefficient of Friction

COMFORT LINER MATERIAL	CONTACT MODE SANITARY/IMPACT	MOISTURE COND DRY/SALINE	FIGURE 2 CODE	COF
GENTEX	SANITARY	DRY	BS(1N)D	0.702
GENTEX	SANITARY	SALINE	BS(1N)S	0.718
GENTEX	SANITARY-SANITARY	DRY	BSS(1N)D	1.385
GENTEX	SANITARY-SANITARY	SALINE	BSS(1N)S	1.339
GENTEX	IMPACT	DRY	BI(1N)D	0.56
KAISER	SANITARY	DRY	KS(1N)D	5.59
KAISER	SANITARY	SALINE	KS(1N)S	4.309
KAISER	IMPACT	DRY	KI(1N)D	1.393
GEC	SANITARY	DRY	GS(1N)D	2.36
GEC	SANITARY	SALINE	GS(1N)S	0.849
GEC	IMPACT	DRY	GI(1N)D1	1.453
GEC	IMPACT	DRY	GI(1N)D2	1.393

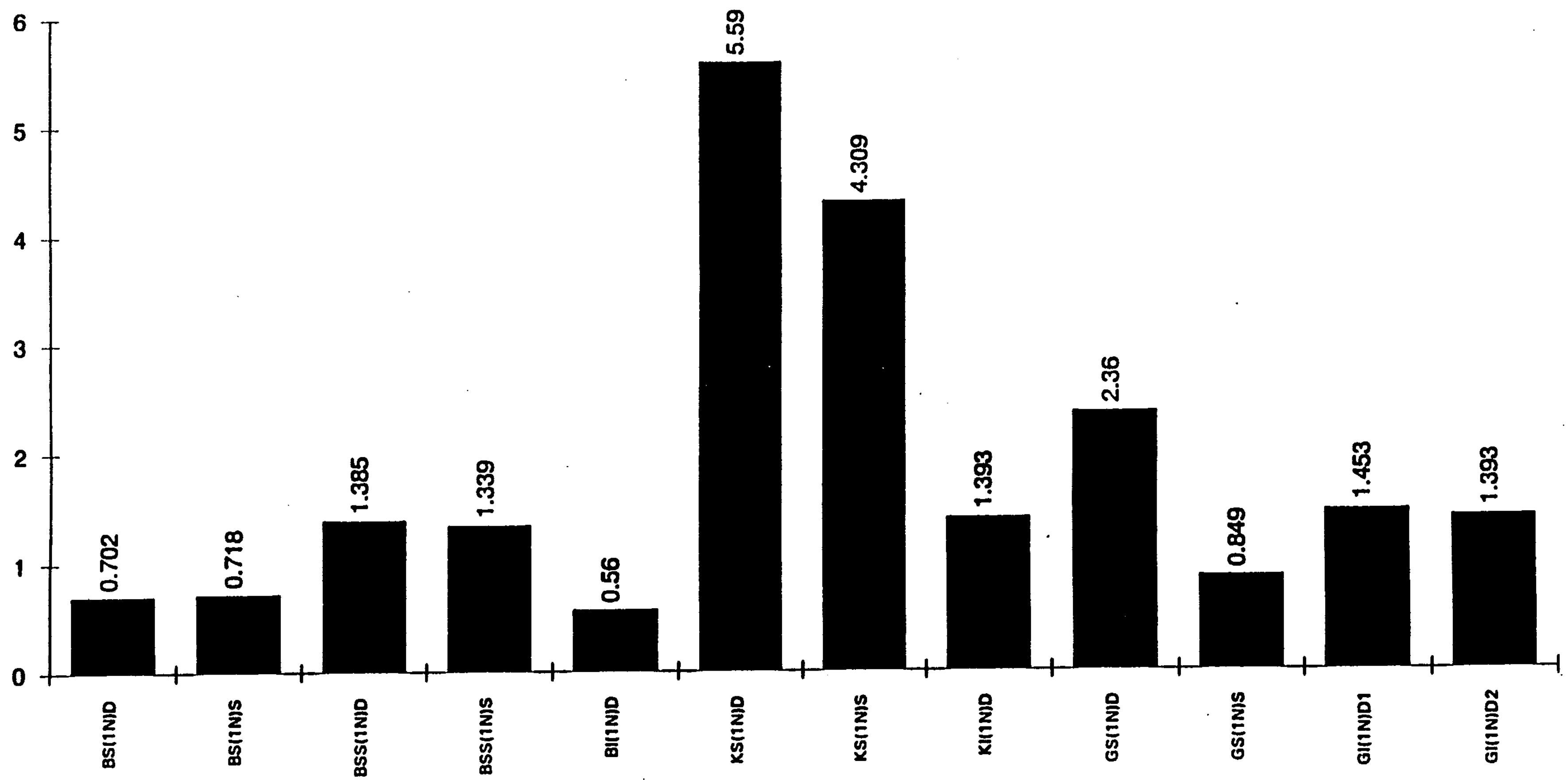

Figure 4. Coefficient of Friction Comparison Plot

SECTION 5.0 CONCLUSIONS

This report has examined the mechanical properties of some commonly used helmet liners. The range of helmet liners examined ran from the low stiffness GEC Marconi foamed-in-place system to the high stiffness Kaiser Electronics TFL comfort liner. This database is useful in understanding the important mechanical properties of current helmet comfort liner systems.

For future advanced helmet comfort liner systems, mechanical properties such as the ones in this report should be generated. Also, the properties generated should be compared to the database in this report to understand how the system will fare in the compromise between pilot comfort and stability.

Table 4. Density Measurement Matrix

GENTEX BUBBLE LINER

Specimen	Area (sq in)	Thickness (in)	Weight (grams)	Density (lb/cu ft)	Date
TP-D-1	1.615	0.188	1.3938	17.47	22-Jun-94
TP-D-2	1.631	0.183	1.1711	14.93	"
TP-D-3	1.626	0.203	1.3261	15.29	"
Avg(S Dev)				15.9(1.1)	

KAISER ELECTRONICS THERMOFORMED LINER

Specimen	Area (sq in)	Thickness (in)	Weight (grams)	Density (lb/cu ft)	Date
TF-D-1	1.617	0.58	0.9324	3.78	24-Jun-94
TF-D-2	1.622	0.573	0.9709	3.98	"
TF-D-3	1.615	0.57	0.9529	3.74	"
Avg(S Dev)				3.83(.10)	

GEC MARCONI SILICONE LINER

Specimen	Area (sq in)	Thickness (in)	Weight (grams)	Density (lb/cu ft)	Date
S-D-1	1.817	0.656	5.1779	16.53	22-Jun-94
S-D-2	1.81	1.00	5.3167	11.18	"
Avg(S Dev)				13.9(2.7)	

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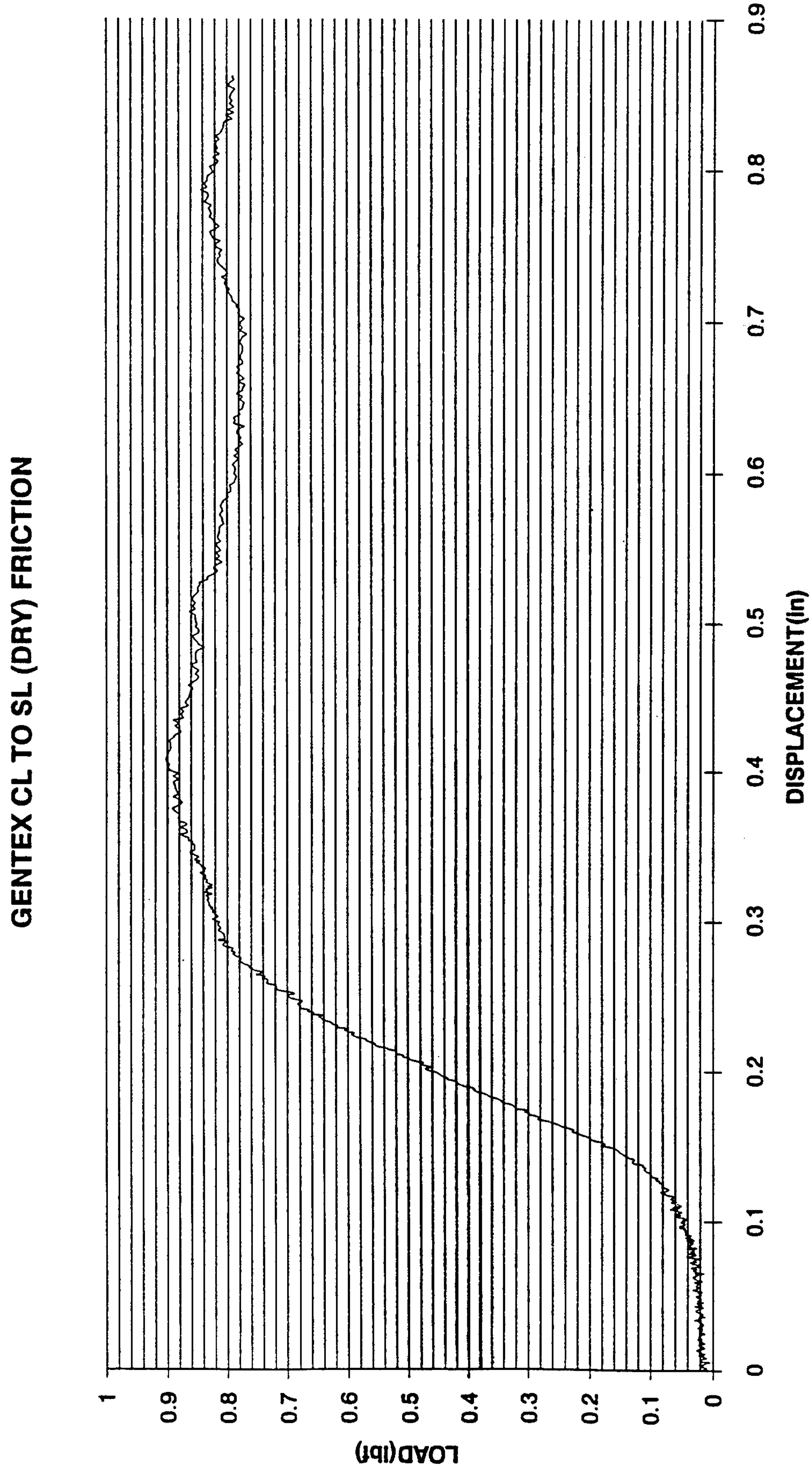
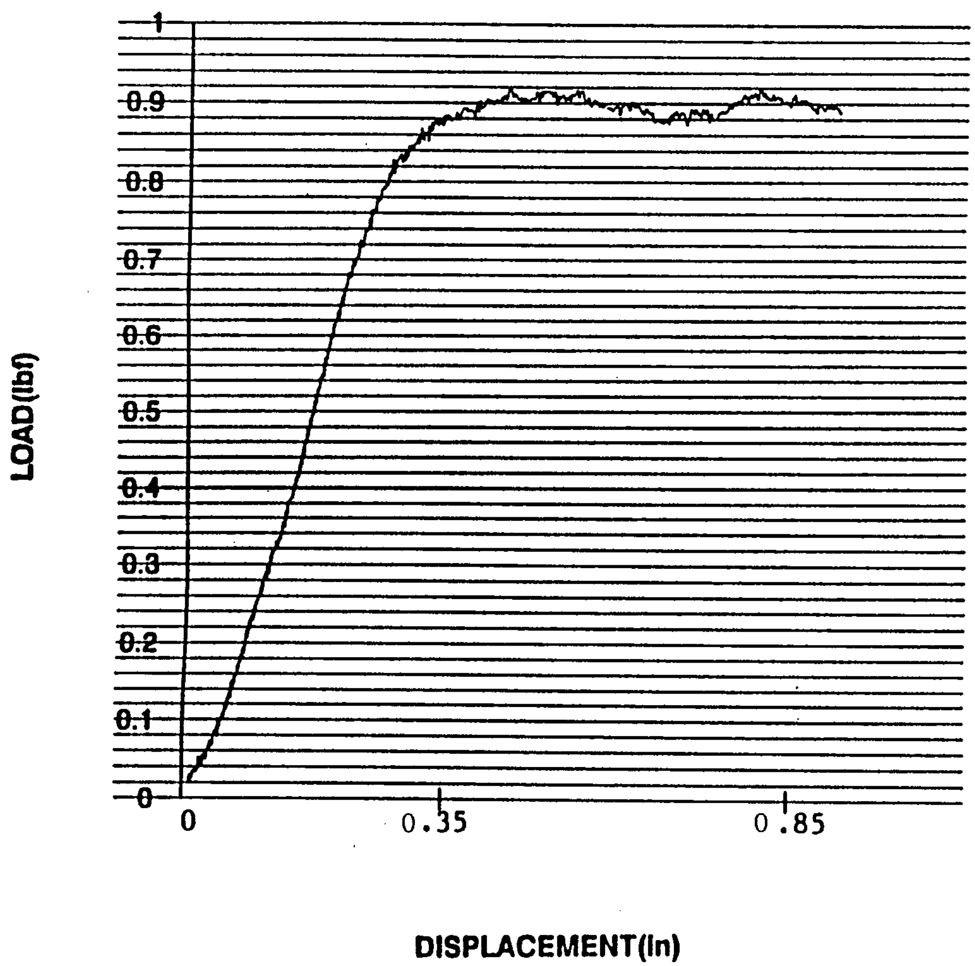
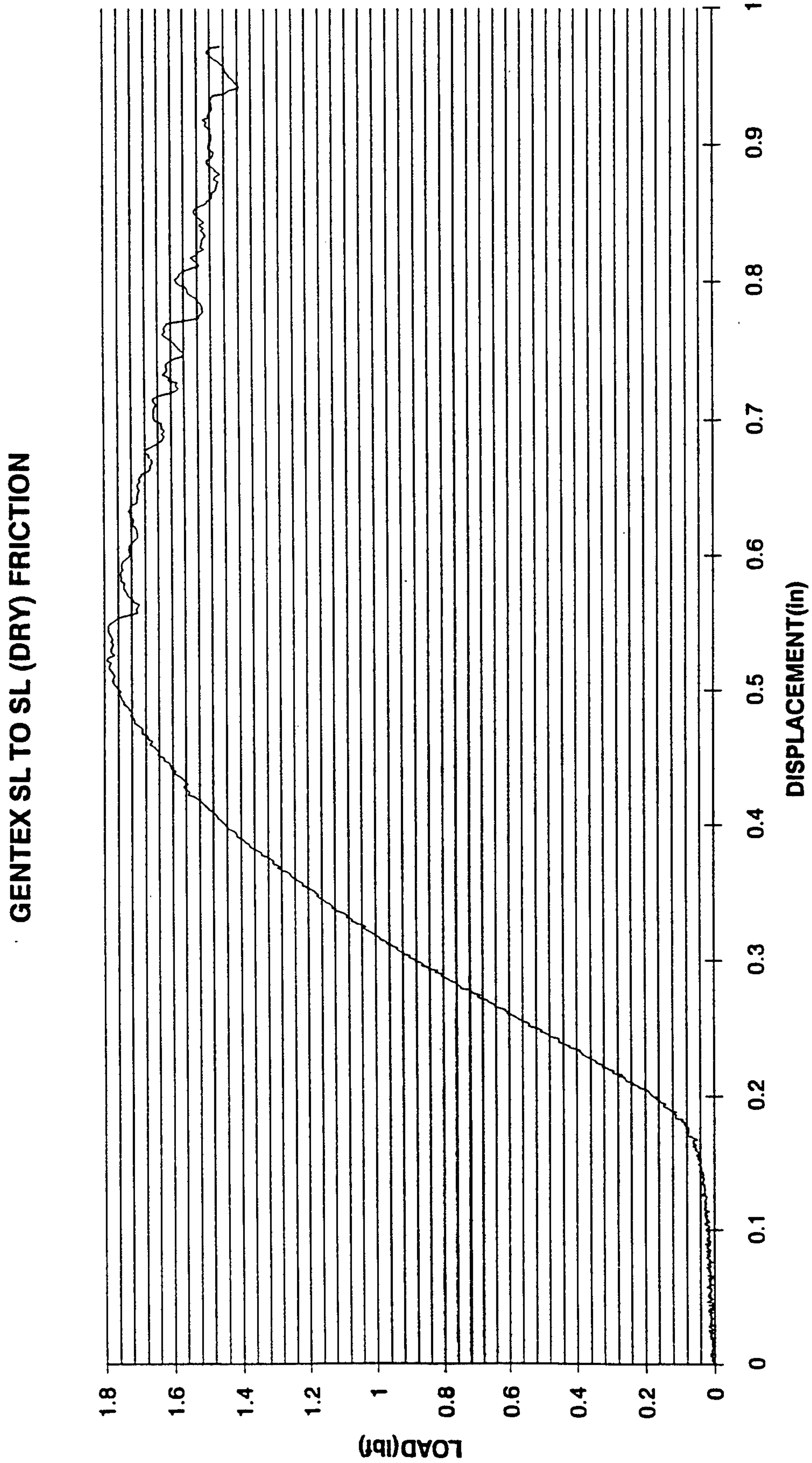
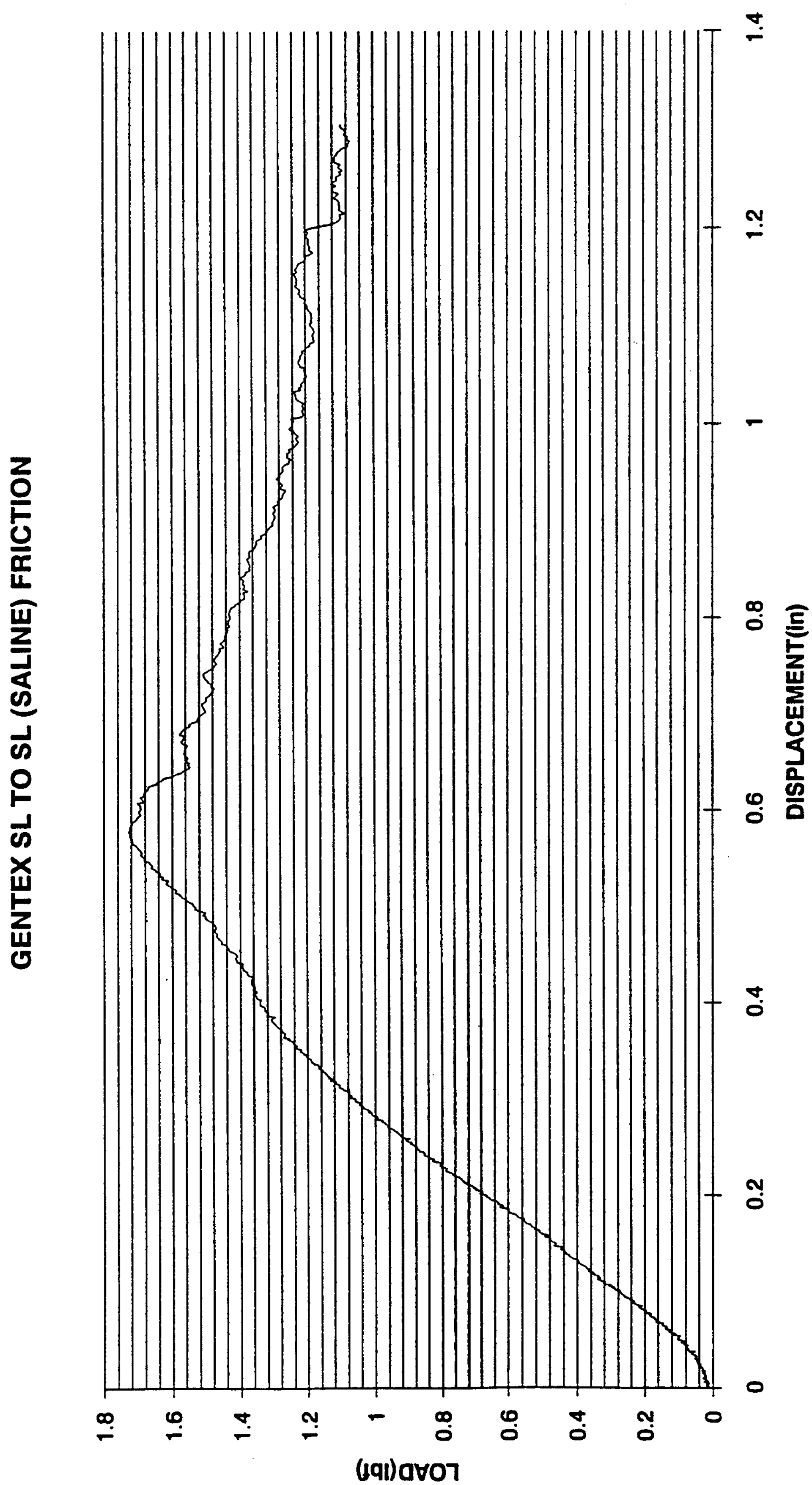
APPENDIX A: COEFFICIENT OF FRICTION PLOTS


GENTEX CL TO SL (DRY) FRICTION
LOAD(lbf)
DISPLACEMENT(in)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

GENTEX CL TO SL (SALINE) FRICTION




GENTEX SL TO SL (DRY) FRICTION
LOAD(lbf)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
DISPLACEMENT(in)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1



GENTEX SL TO SL (SALINE) FRICTION
LOAD(lbf)
DISPLACEMENT(In)
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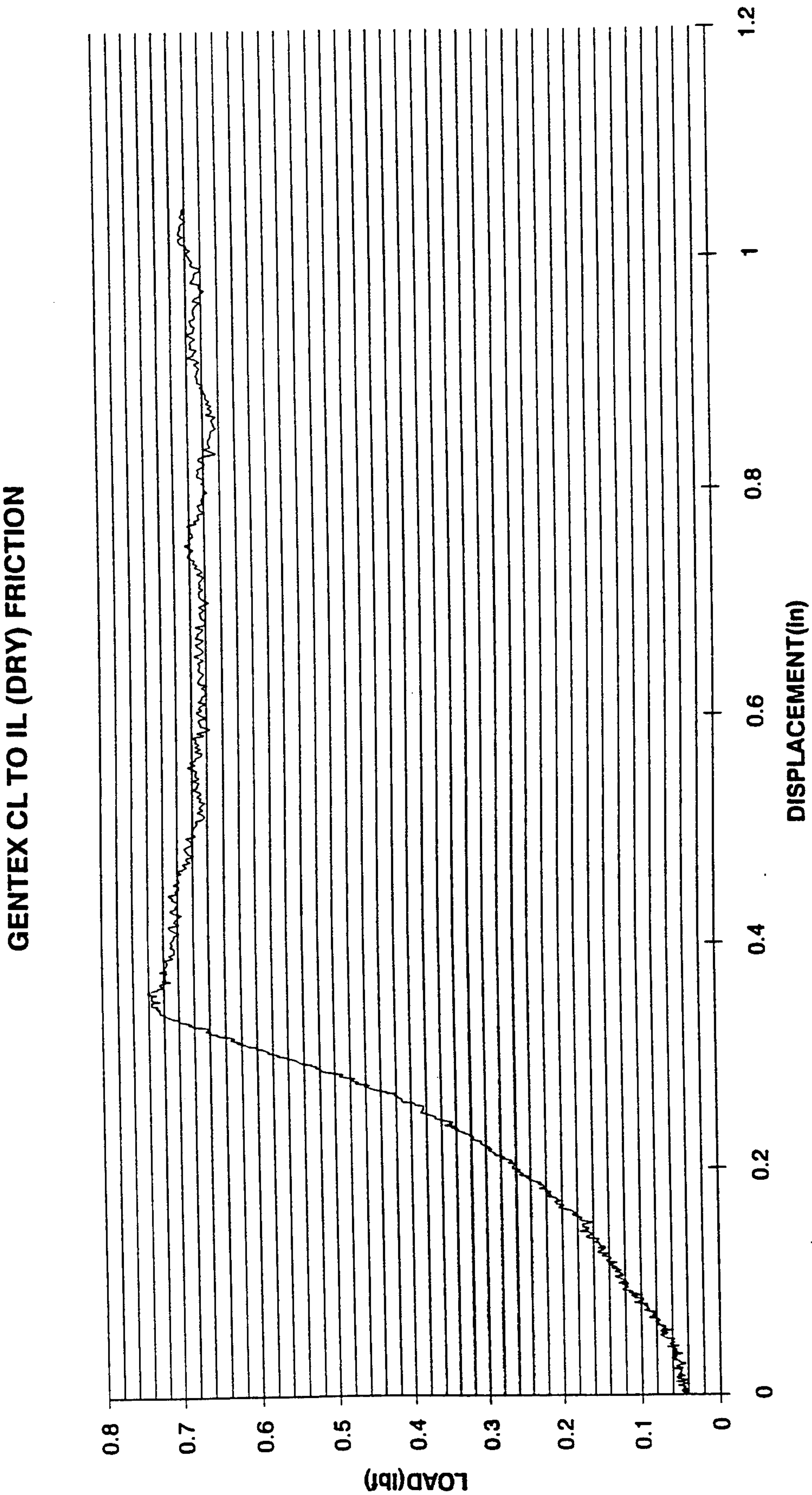
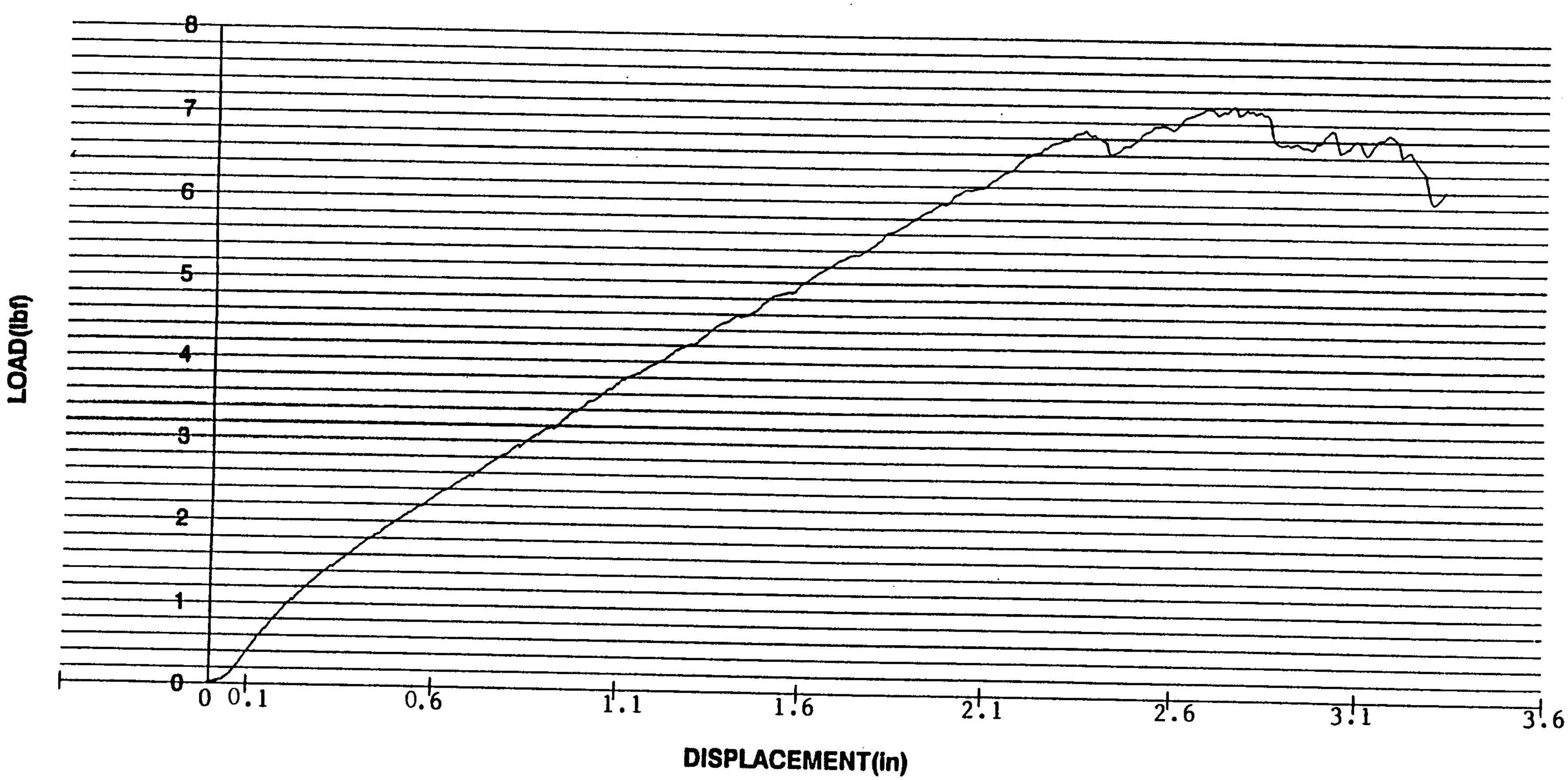
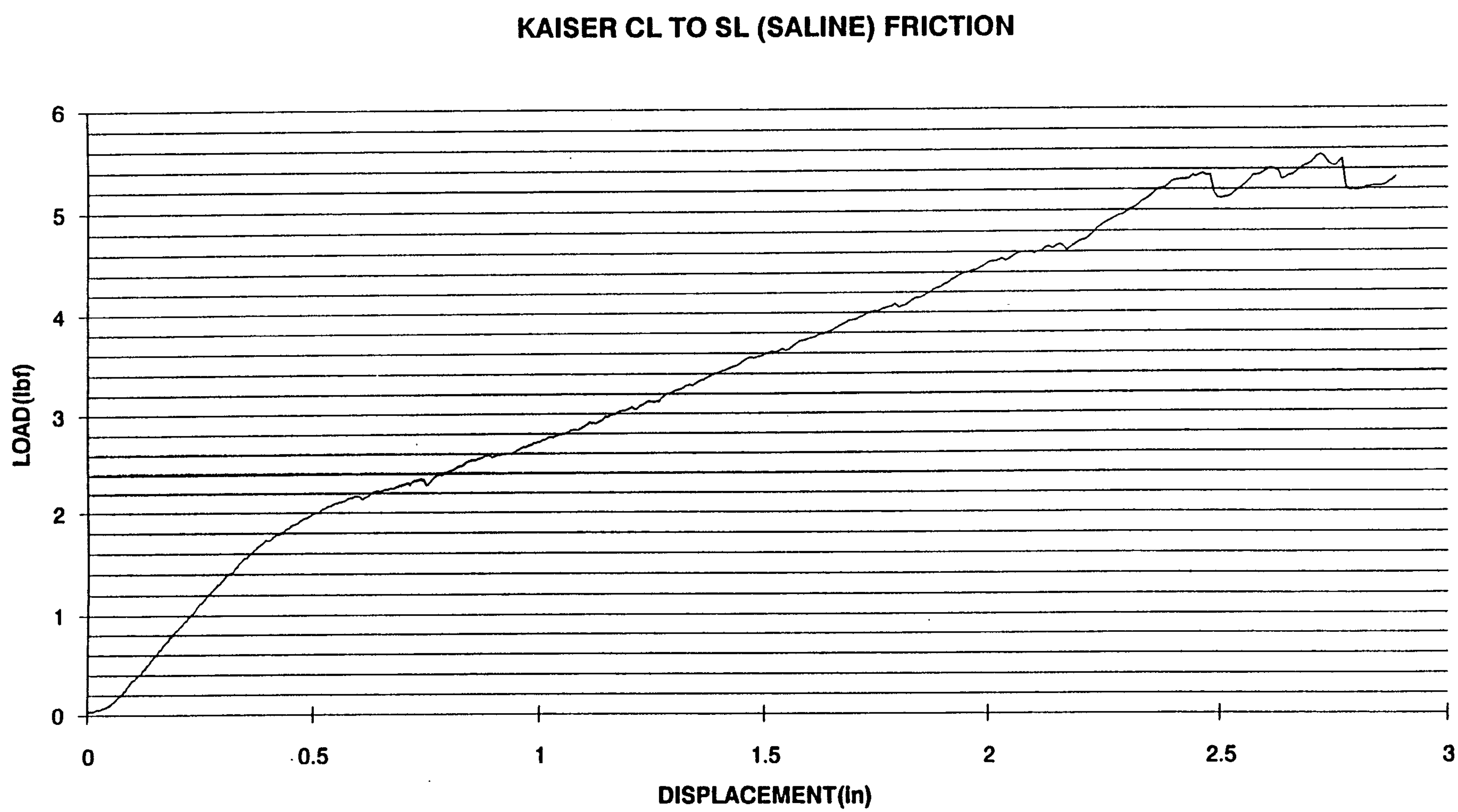
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

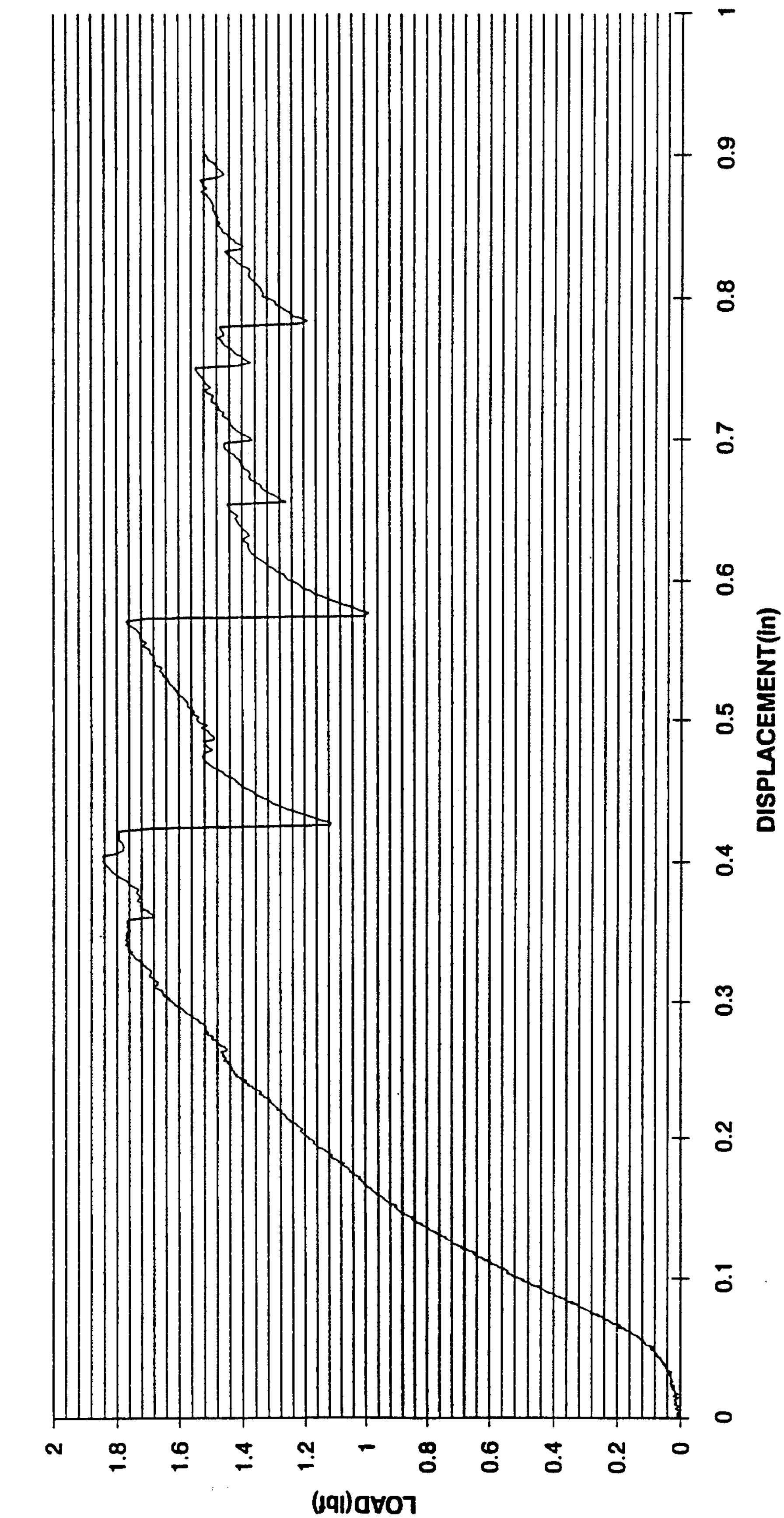

GENTEX CL TO IL (DRY) FRICTION
LOAD(lbf)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
DISPLACEMENT(in)
0
0.2
0.4
0.6
0.8
1
1.2

KAISER CL TO SL (DRY) FRICTION




KAISER CL TO SL (SALINE) FRICTION
LOAD(lbf)
6
5
4
3
2
1
0
0
0.5
1
1.5
2
2.5
3
DISPLACEMENT(In)

KAISER CL TO IL (DRY) FRICTION



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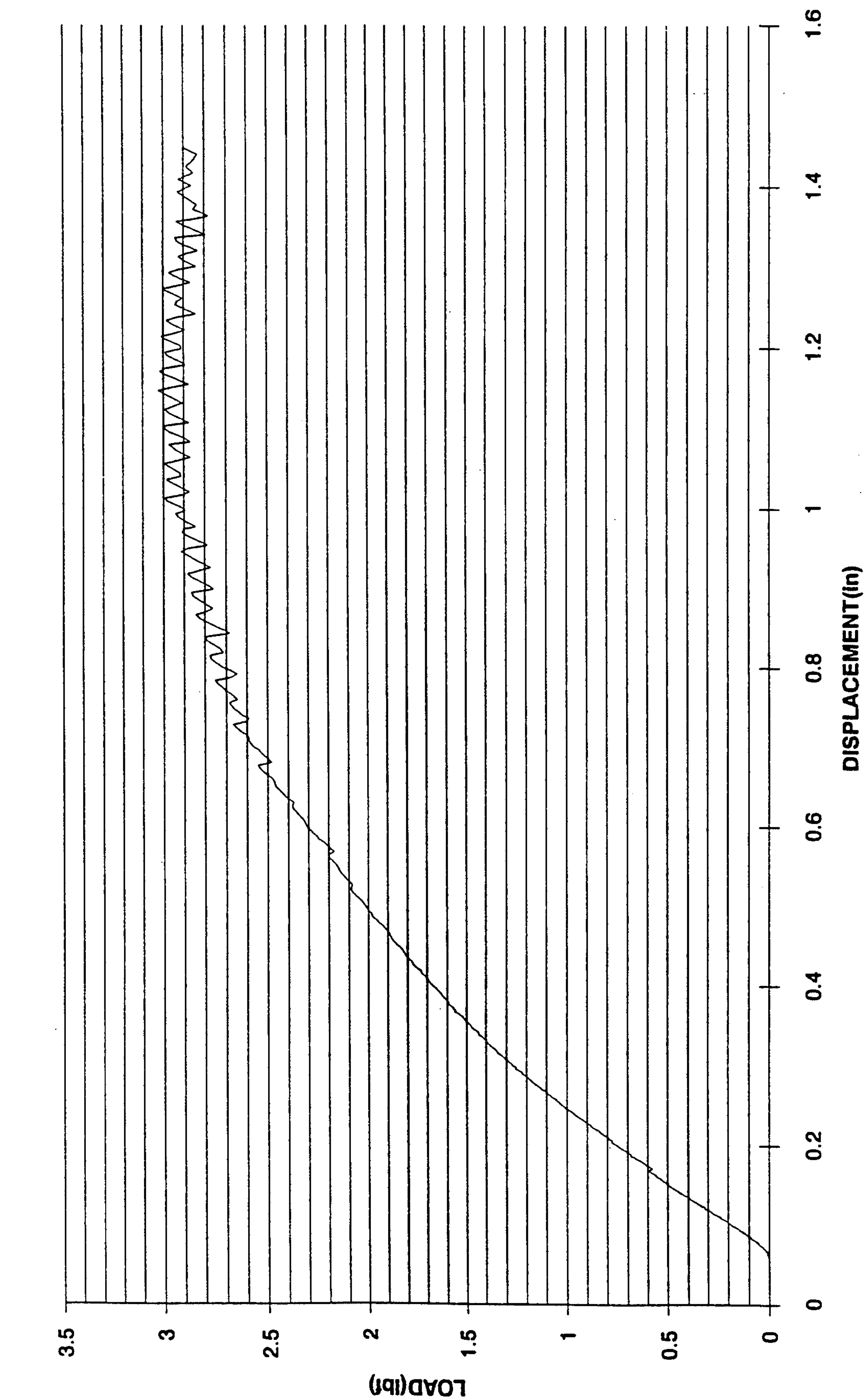
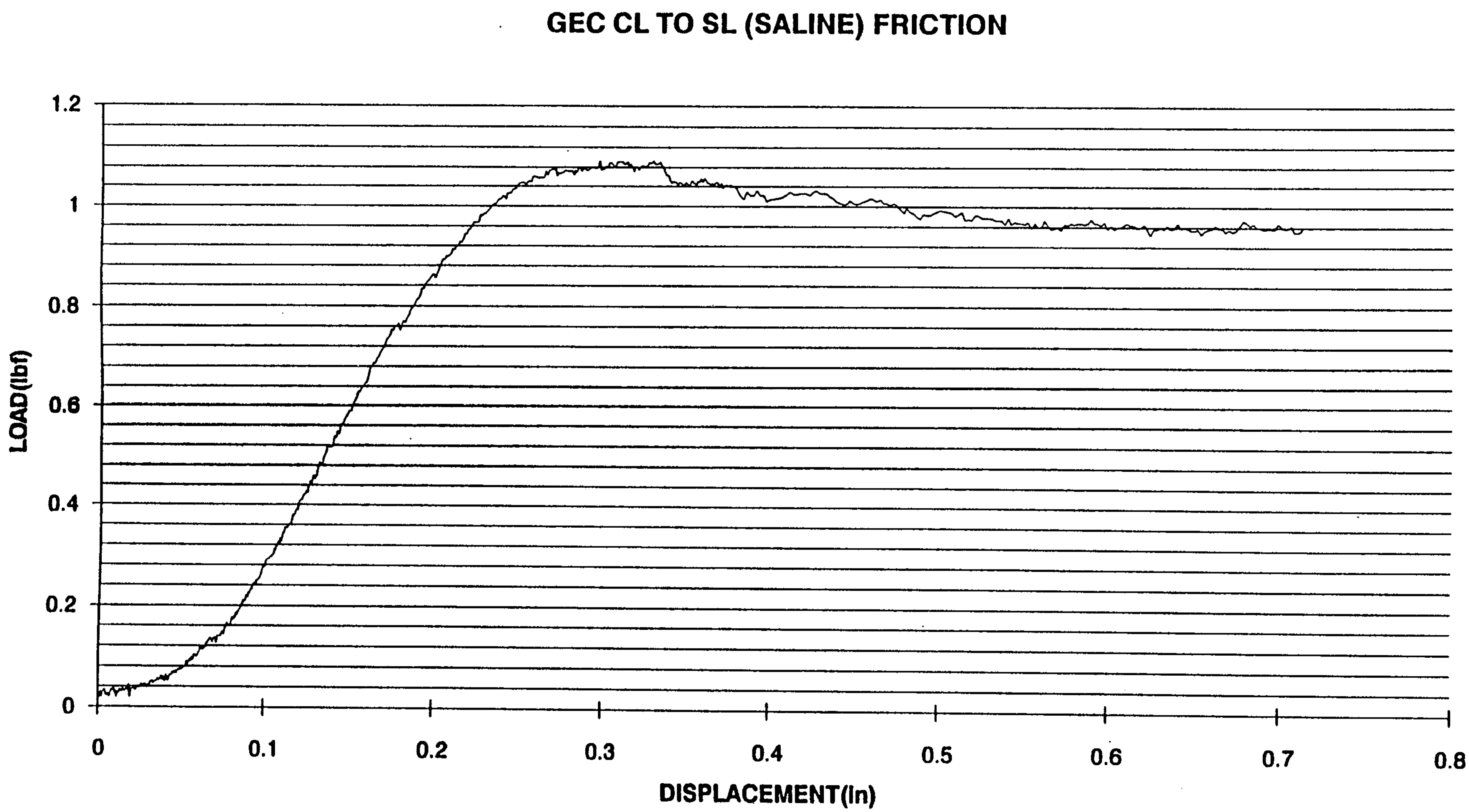
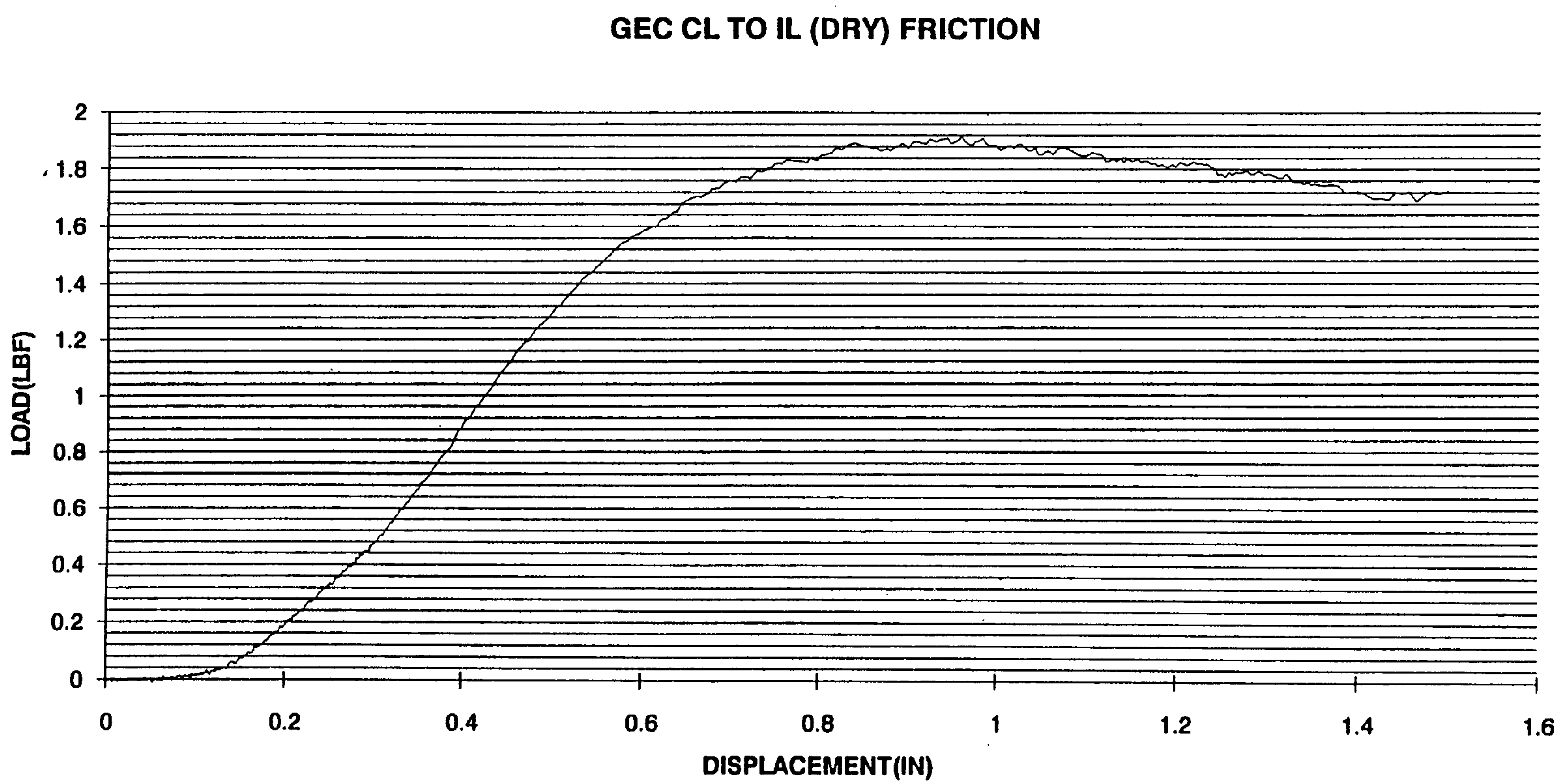
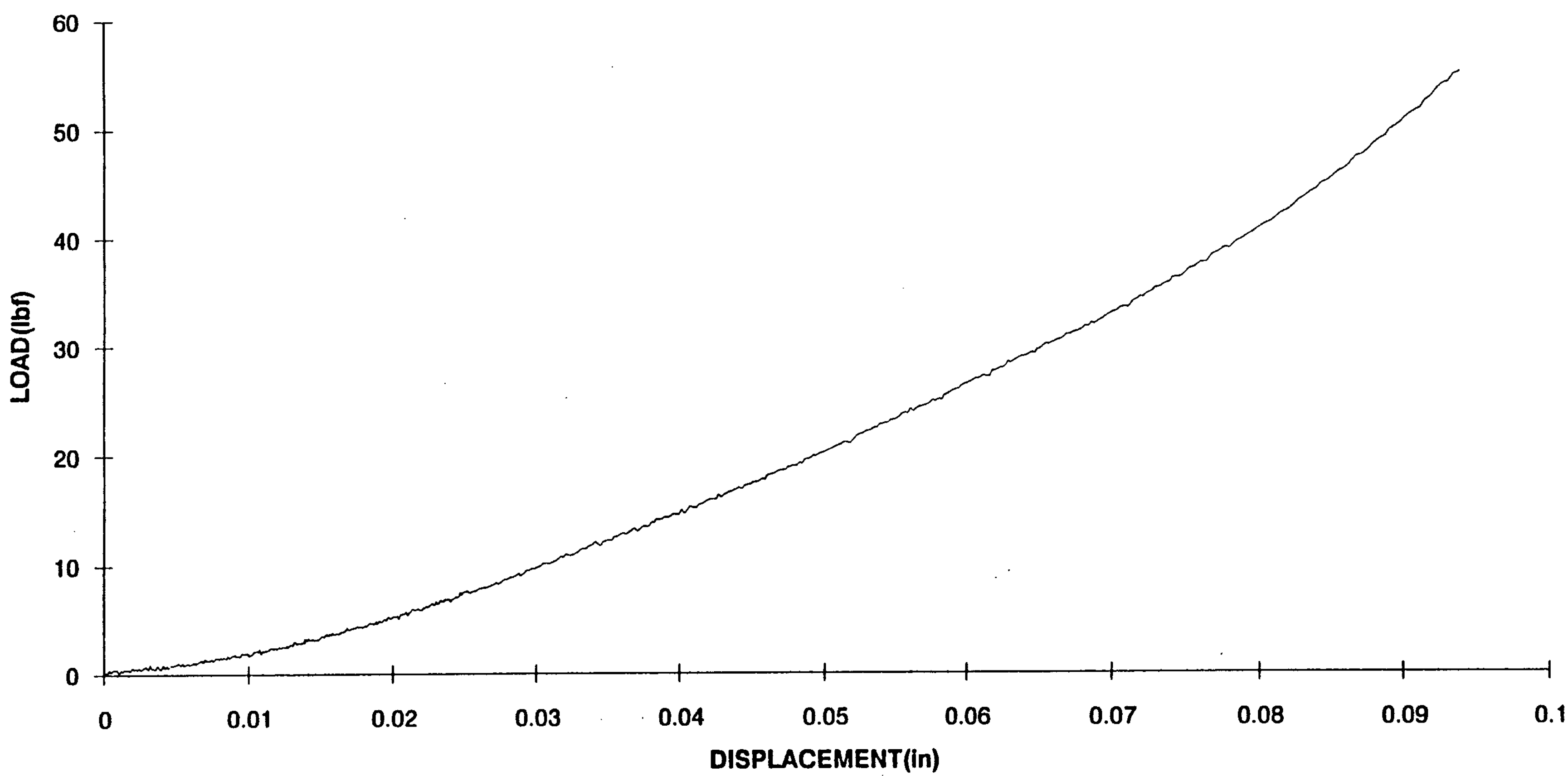


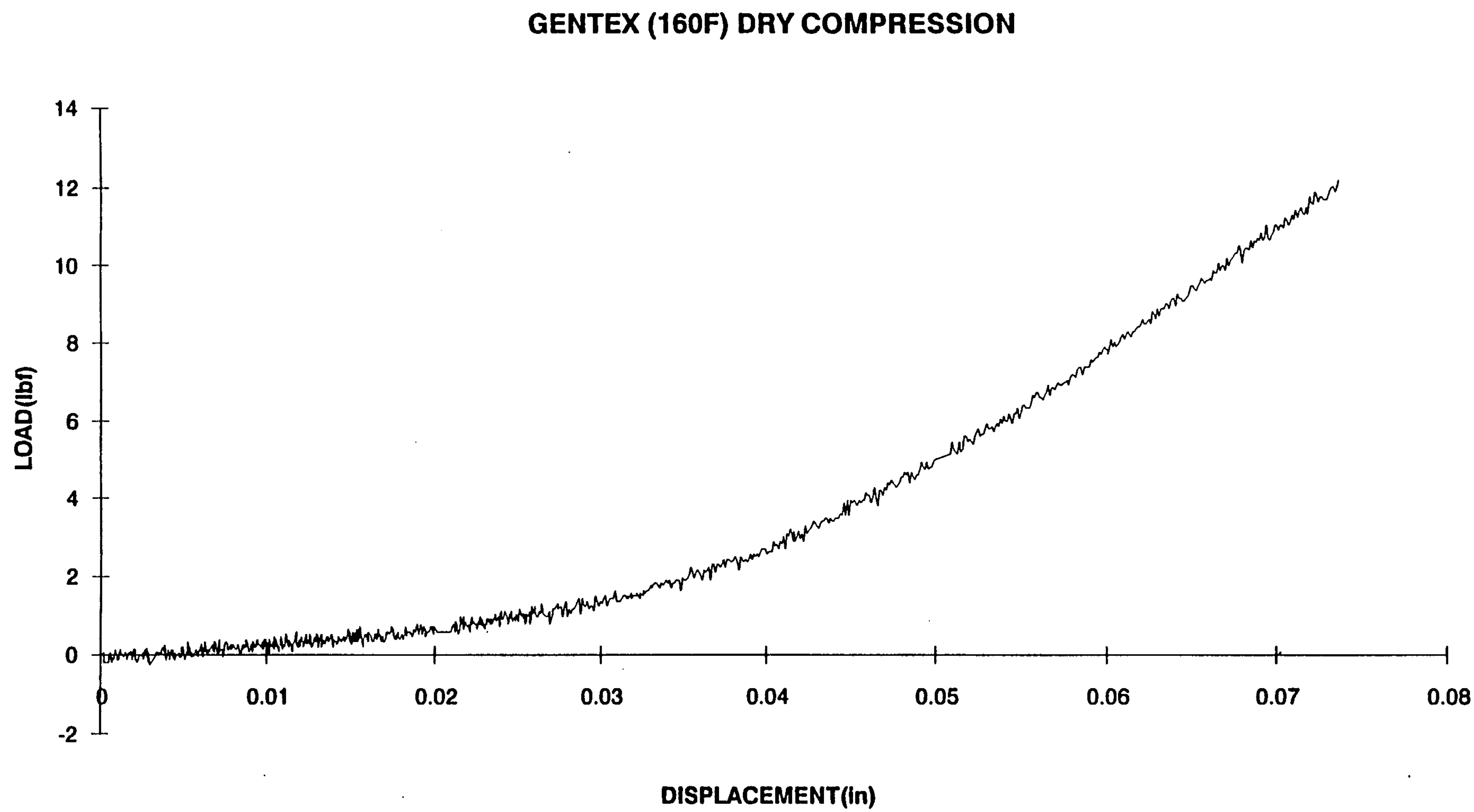

GEC CL TO SL (SALINE) FRICTION
1.2
1
0.8
0.6
0.4
0.2
0
LOAD(lbf)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
DISPLACEMENT(In)

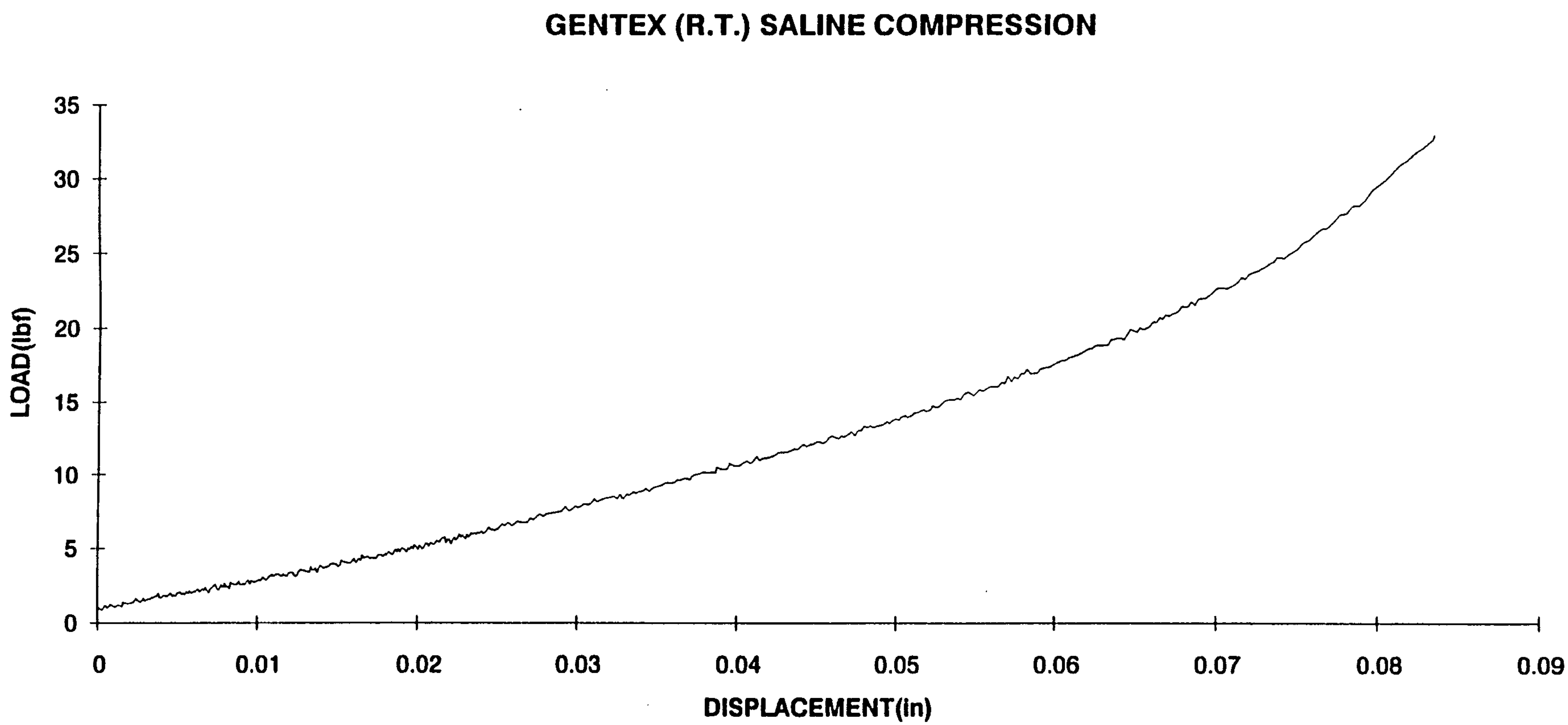

GEC CL TO IL (DRY) FRICTION
LOAD(LBF)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
DISPLACEMENT(IN)

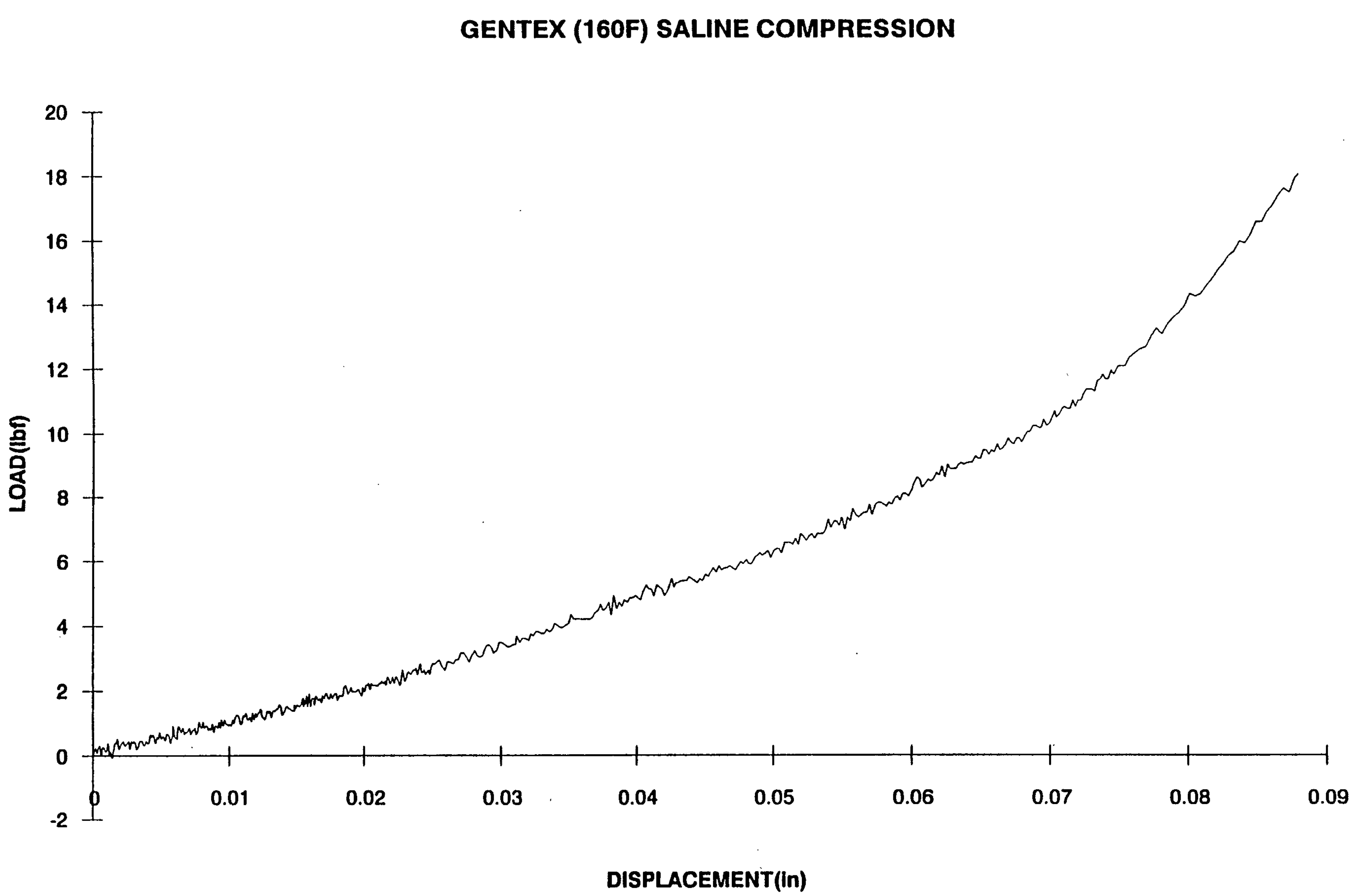
APPENDIX B: COMPRESSION TESTING PLOTS

GENTEX (R.T.) DRY COMPRESSION



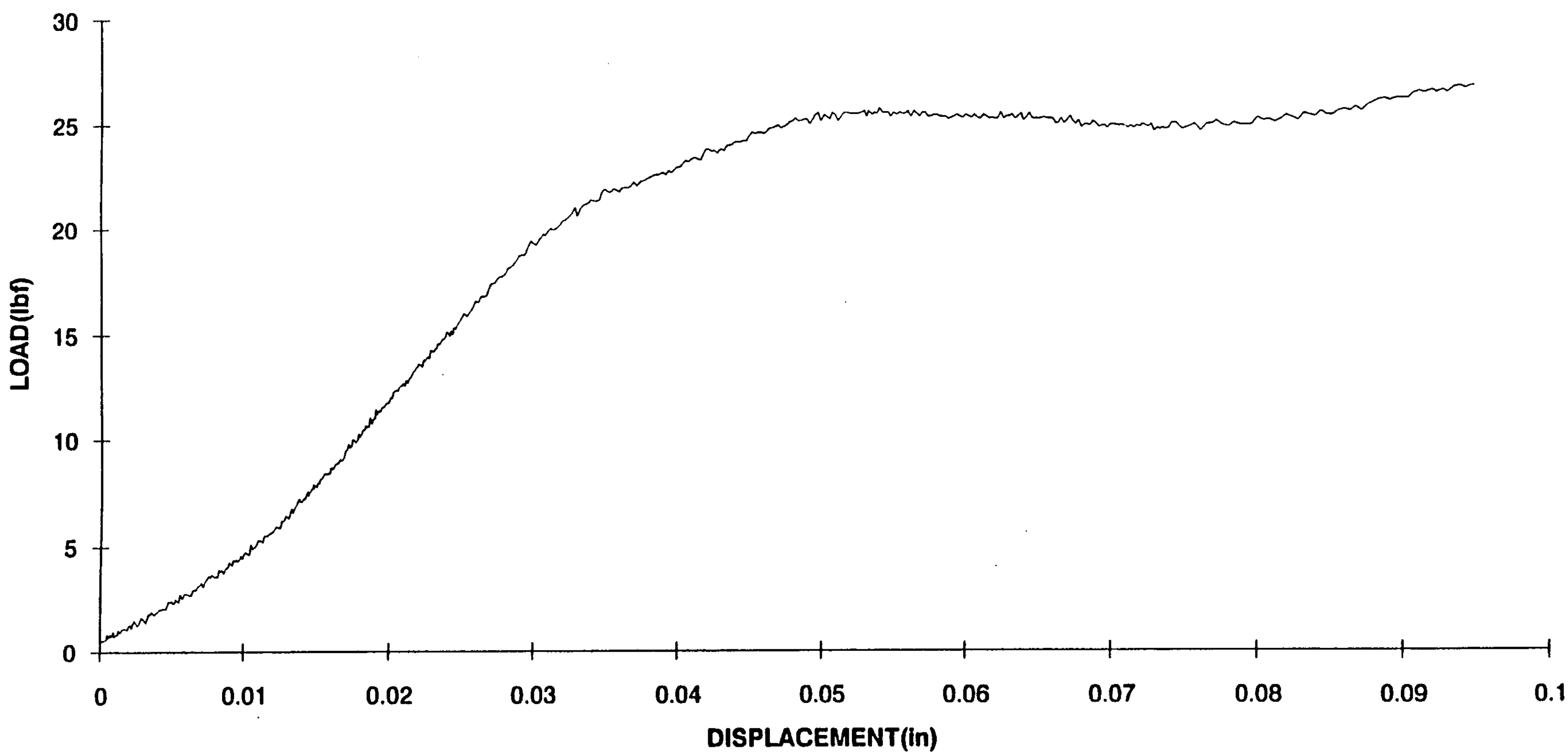

GENTEX (160F) DRY COMPRESSION
LOAD(lbf)
14
12
10
8
6
4
2
0
-2
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
DISPLACEMENT(in)

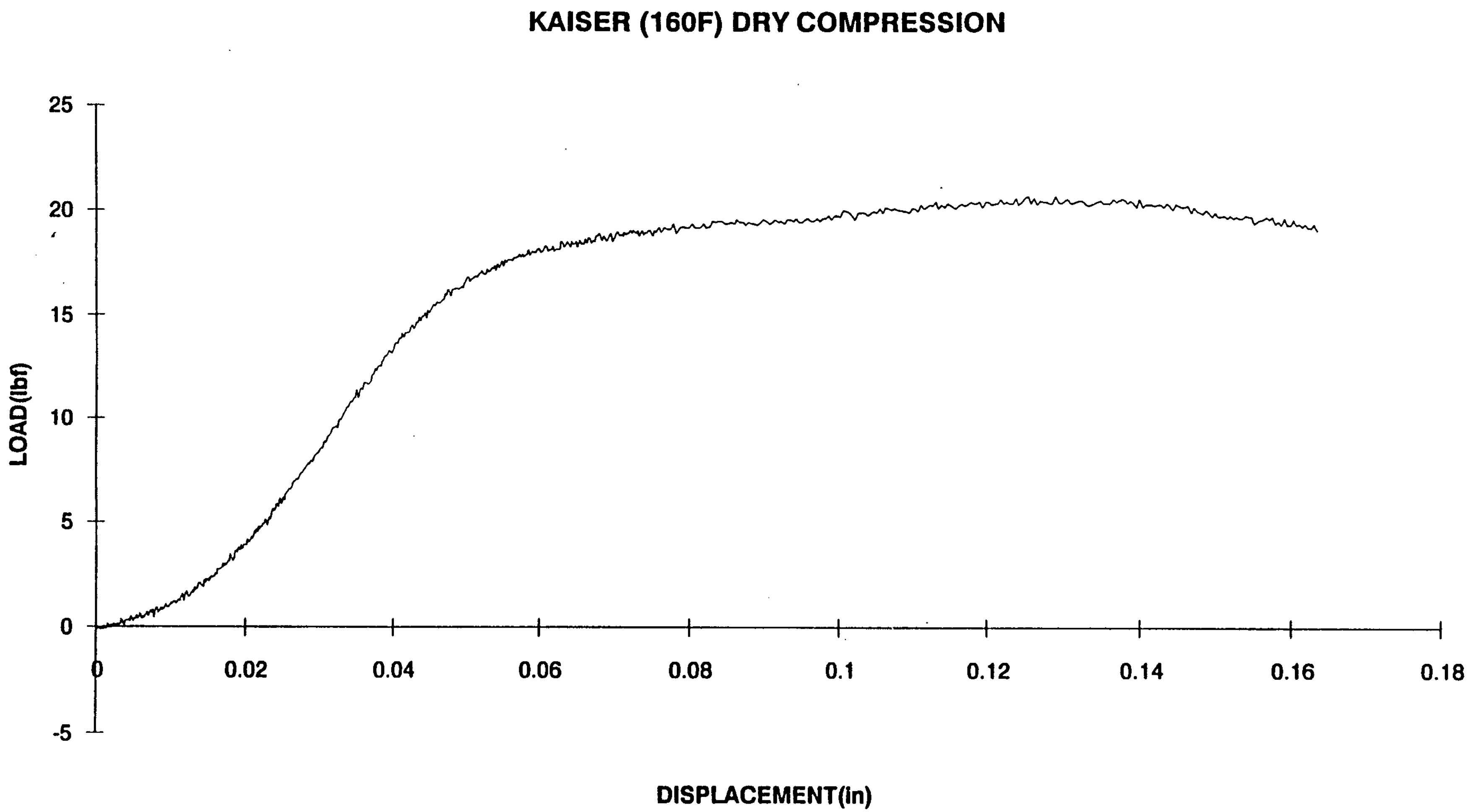

GENTEX (R.T.) SALINE COMPRESSION
LOAD(lbf)
35
30
25
20
15
10
5
0
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
DISPLACEMENT(in)



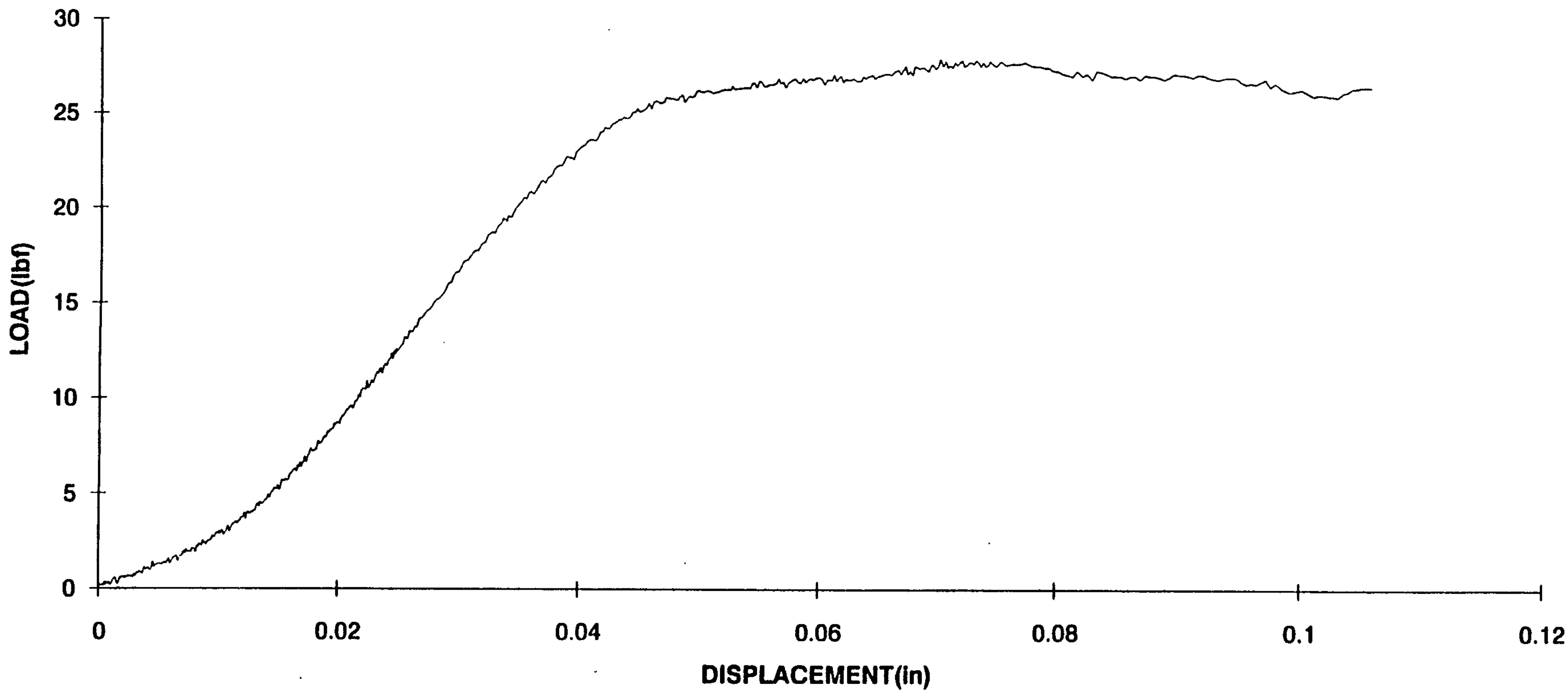
GENTEX (160F) SALINE COMPRESSION
LOAD(lbf)
20
18
16
14
12
10
8
6
4
2
0
-2
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
DISPLACEMENT(in)

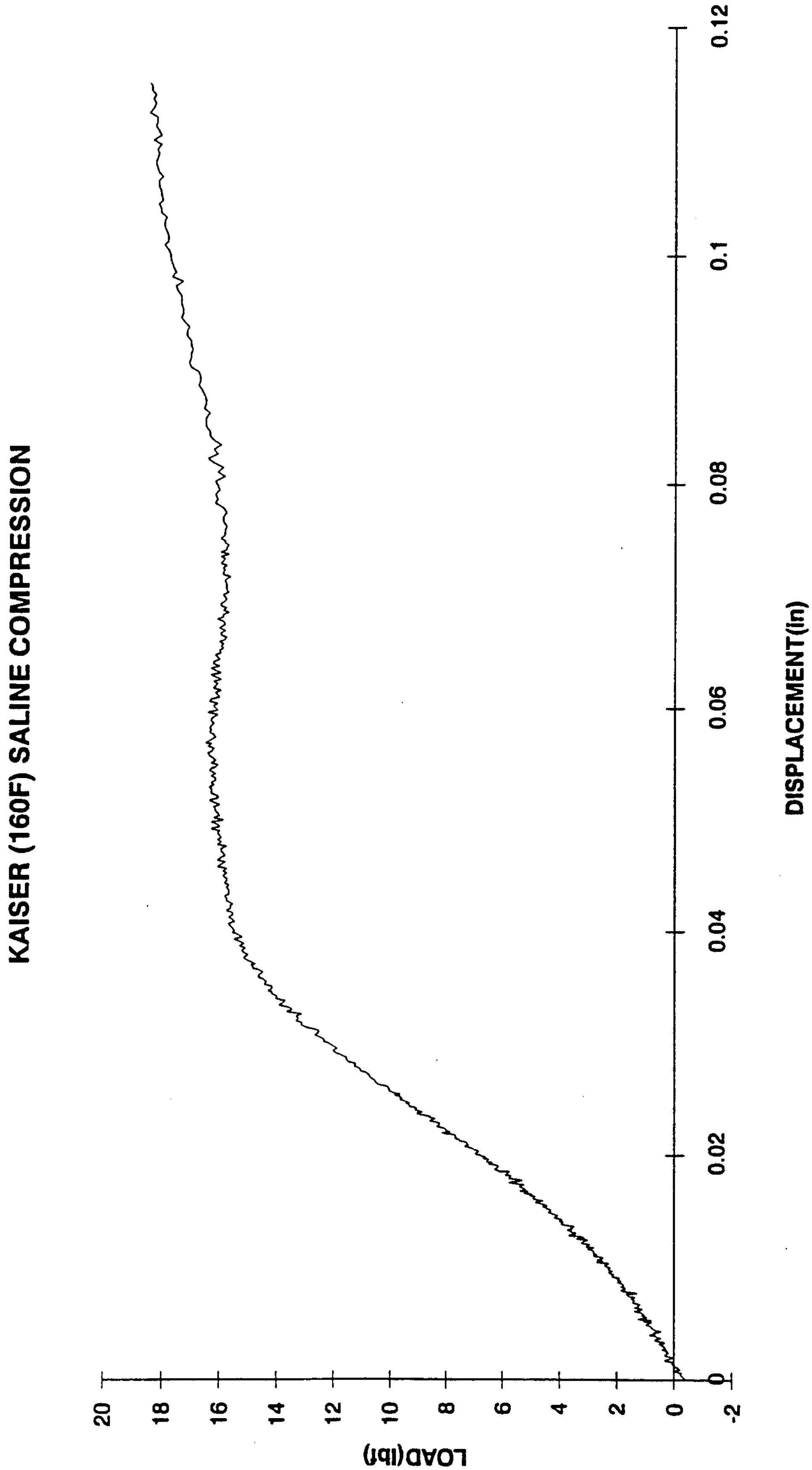
KAISER (R.T.) DRY COMPRESSION



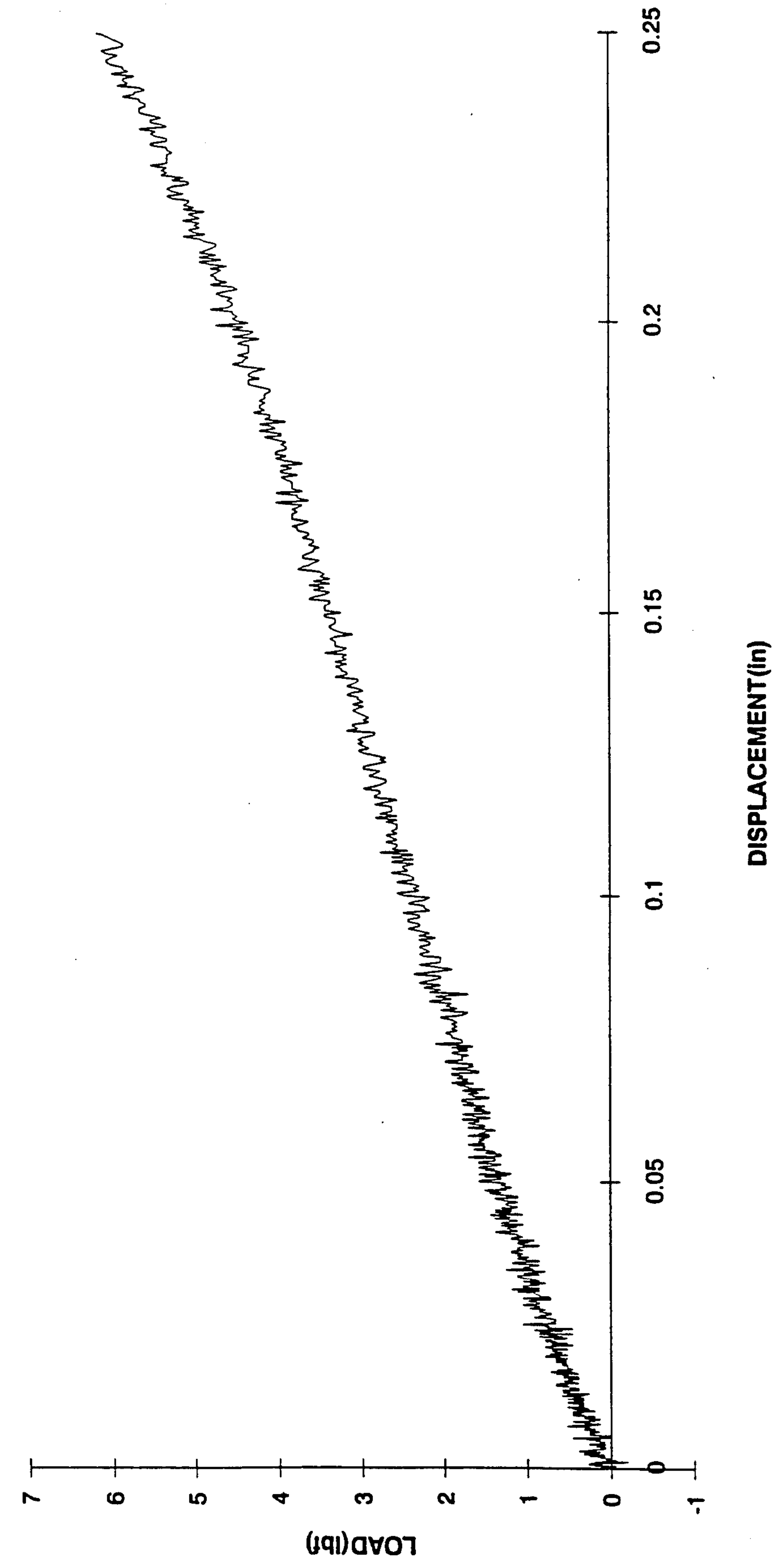

KAISER (160F) DRY COMPRESSION
LOAD(lbf)
25
20
15
10
5
0
-5
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
DISPLACEMENT(in)

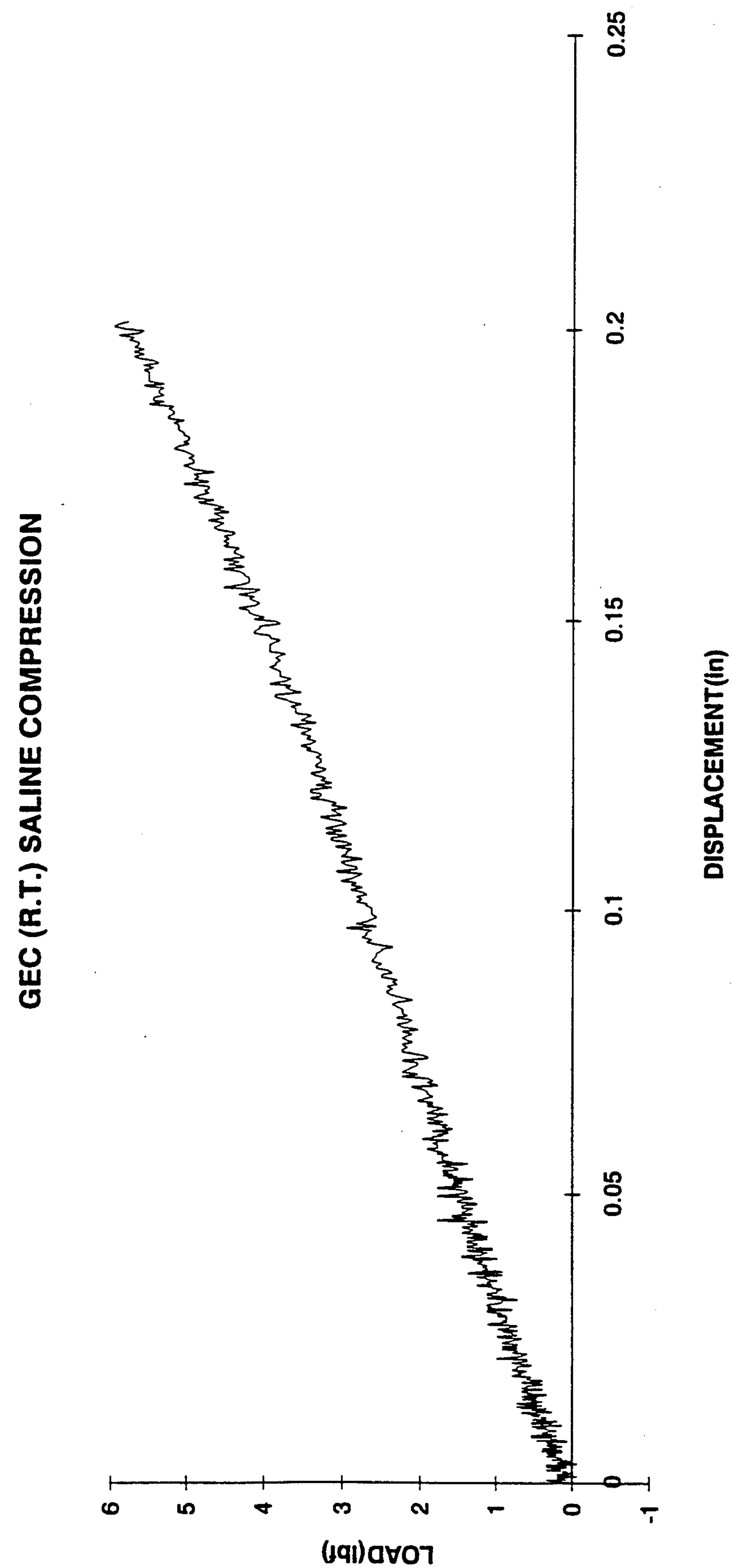
KAISER (R.T.) SALINE COMPRESSION

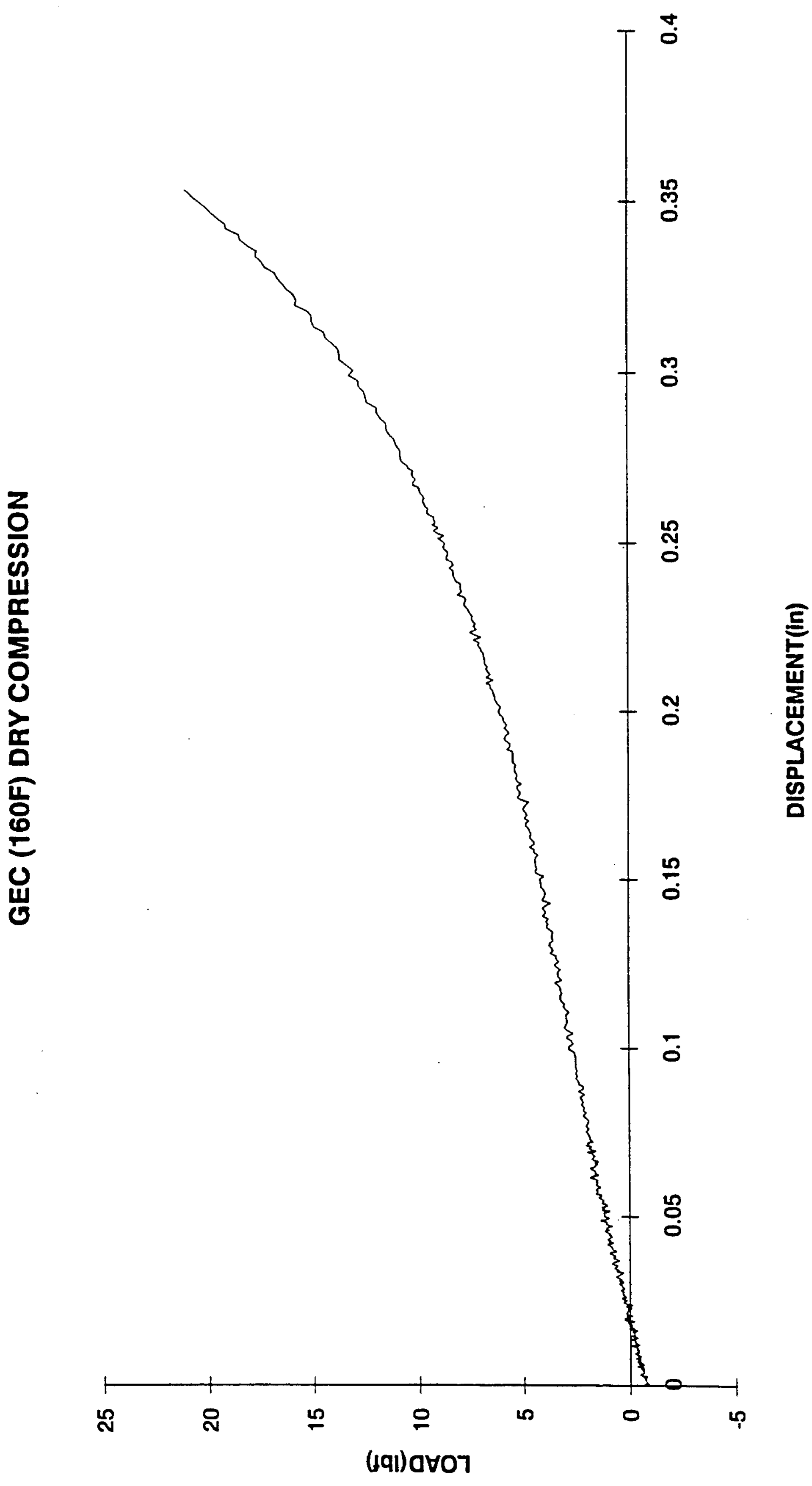


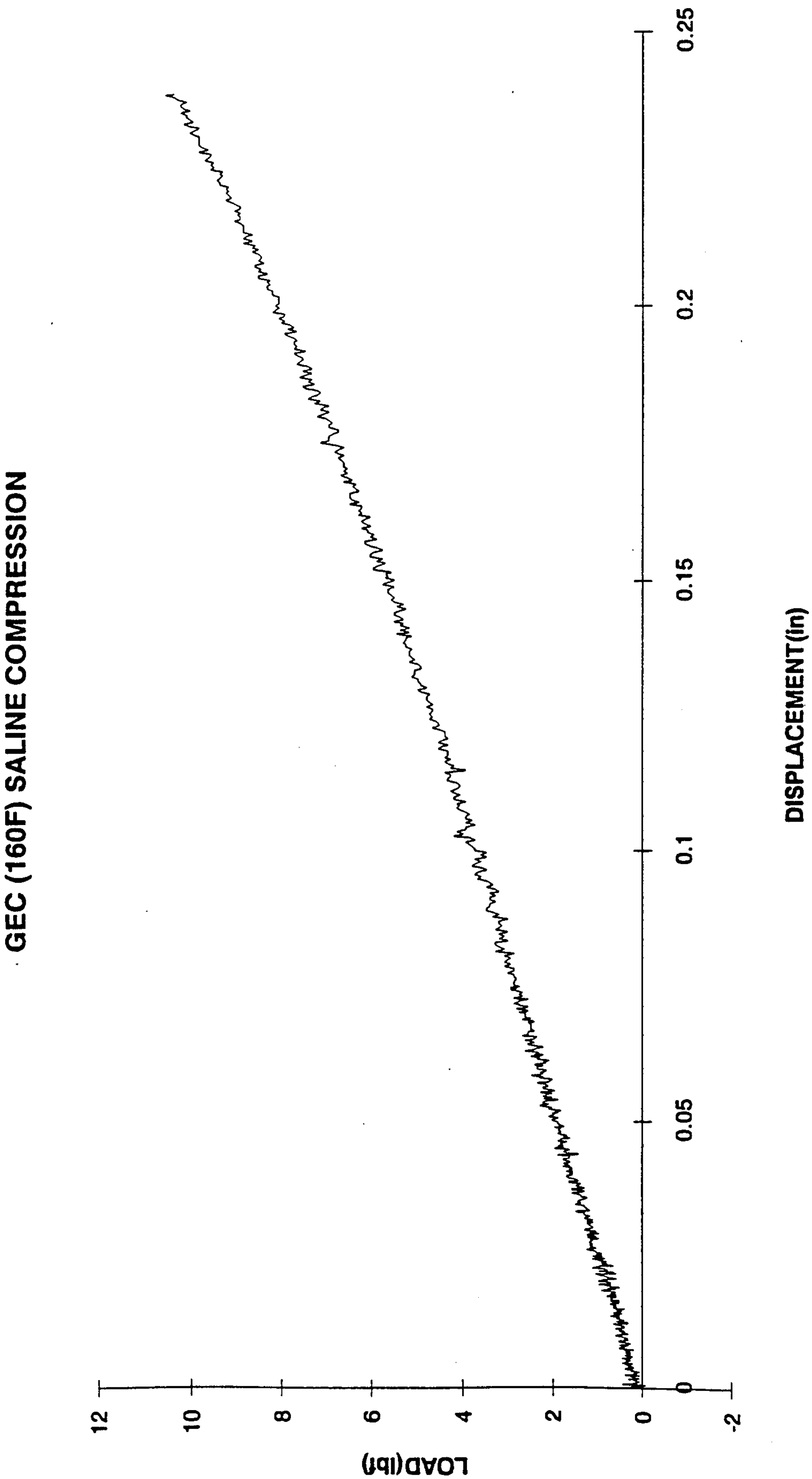

KAISER (160F) SALINE COMPRESSION
LOAD(lbf)
20
18
16
14
12
10
8
6
4
2
0
-2
0
0.02
0.04
0.06
0.08
0.1
0.12
DISPLACEMENT(in)

GEC (R.T.) DRY COMPRESSION




GEC (R.T.) SALINE COMPRESSION
LOAD(lbf)
DISPLACEMENT(in)
6
5
4
3
2
1
0
-1
0.05
0.1
0.15
0.2
0.25


GEC (160F) DRY COMPRESSION
LOAD(lbf)
25
20
15
10
5
0
-5
DISPLACEMENT(in)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4


GEC (160F) SALINE COMPRESSION
LOAD(lbf)
12
10
8
6
4
2
0
-2
0
0.05
0.1
0.15
0.2
0.25
DISPLACEMENT(in)